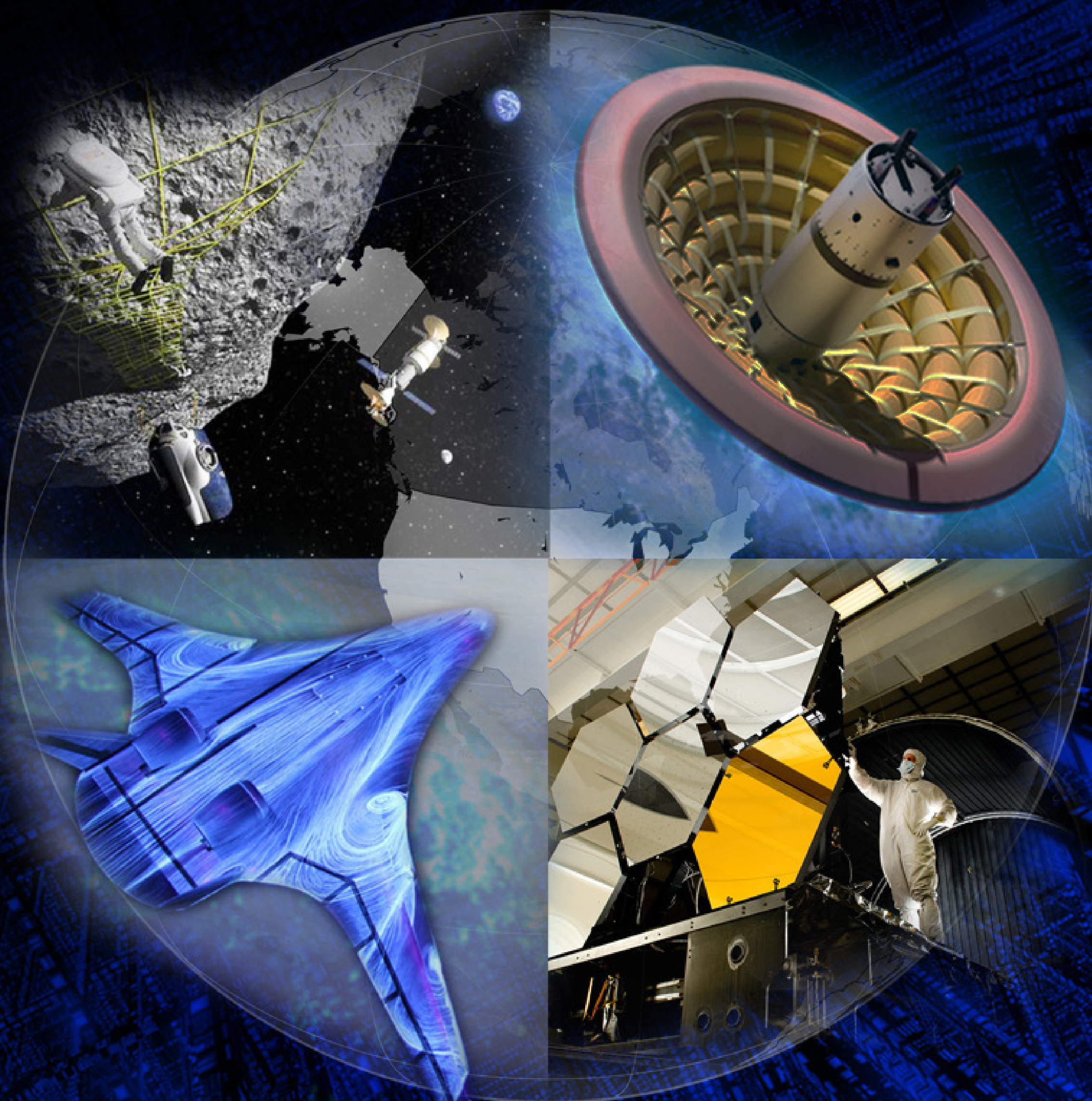
National Aeronautics and Space Administration

NASA Technology Roadmaps
TA 2: In-Space Propulsion Technologies



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Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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Executive Summary

This is Technology Area (TA) 2: In-Space Propulsion Technologies, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

A large fraction of the rocket engines in use today are chemical rockets; that is, they obtain the energy needed to generate thrust by chemical reactions to create a hot gas that is expanded to produce thrust. Thrust-to-weight ratios greater than unity are required to launch from the surface of the Earth, and chemical propulsion is currently the only flight-qualified propulsion technology capable of producing the magnitude of thrust necessary to overcome Earth’s gravity.

Numerous concepts for advanced in-space propulsion technologies have been developed over the past 50 years. While generally providing at least an order of magnitude higher specific impulse (I_{sp}) (thrust efficiency) compared to chemical engines, the advanced concepts typically generate much lower values of thrust. Advanced propulsion technologies, such as electric propulsion, are commonly used for station keeping on commercial communications satellites and for prime propulsion on some scientific missions because they have significantly higher values of I_{sp}.

There is no single propulsion technology that will benefit all missions or mission types. The requirements for in-space propulsion vary widely due to their intended application. The technology candidates described herein will support everything from small satellites and robotic deep-space exploration to space stations and human missions to Mars.

Goals

The overall goals for developing in-space propulsion technologies are to create improvements in thrust levels, I_{sp}, power, specific mass (or specific power), volume, system mass, system complexity, operational complexity, commonality with other spacecraft systems, manufacturability, durability, safety, reliability, and cost. The in-space propulsion needs of any given mission (or mission class) are highly dependent upon the mission architecture, and there is no “one size fits all” technology solution that will work for all missions or even all mission classes. The development of higher-power electric propulsion, nuclear thermal propulsion, and cryogenic chemical propulsion will have the broadest overall impact on enabling or enhancing missions across each class.

Table 1. Summary of Level 2 TAs

2.0 In-Space Propulsion Technologies	**Goals:**	**Enhance current missions and open up new mission opportunities through improvements in performance, manufacturability, durability, and cost; and development of new propulsion capabilities.**
2.1 Chemical Propulsion	Sub-Goals:	Improve performance, reliability, and safety.
2.2 Non-Chemical Propulsion	Sub-Goals:	Improve performance and lifetime. Enable mission opportunities with efficient alternatives to chemical propulsion.
2.3 Advanced (TRL < 3) Propulsion Technologies	Sub-Goals:	Provide propulsion capabilities to enable missions that are not feasible using current propulsion solutions.
2.4 Supporting Technologies	Sub-Goals:	Improve the capability of propulsion systems to increase the efficiency and flexibility of exploration and science missions.

Benefits

A wide range of candidate chemical and advanced in-space propulsion technologies with diverse characteristics can benefit future missions. Chemical propulsion technology developments will reduce the human risk factors and increase the efficiency and reliability of the systems, which will reduce costs for future missions. Advanced in-space propulsion technologies will result in much more effective exploration of our solar system, and will permit mission designers to plan missions to fly anytime, anywhere, and complete a host of science objectives at their destinations.

More capable and efficient in-space propulsion will benefit NASA, other government agencies, and the commercial space industry—virtually any organization that builds or uses space satellites. In-space propulsion is a category of technology where developments can benefit a number of critical figures of merit (metrics) for space exploration. Space exploration is about getting to new places (mission enabling), getting there safely (increased reliability), getting there quickly (reduced transit times), sending a lot of mass there (increased payload mass), and getting there cheaply (lower cost). The simple act of "getting" there requires employing an in-space propulsion system, and the other metrics are modifiers to this fundamental action.

Improvements derived from technology candidates within this TA will decrease transit times, increase payload mass, provide safer spacecraft, and decrease costs. In some instances, developing technology candidates within this TA will result in mission-enabling breakthroughs that will revolutionize space exploration.

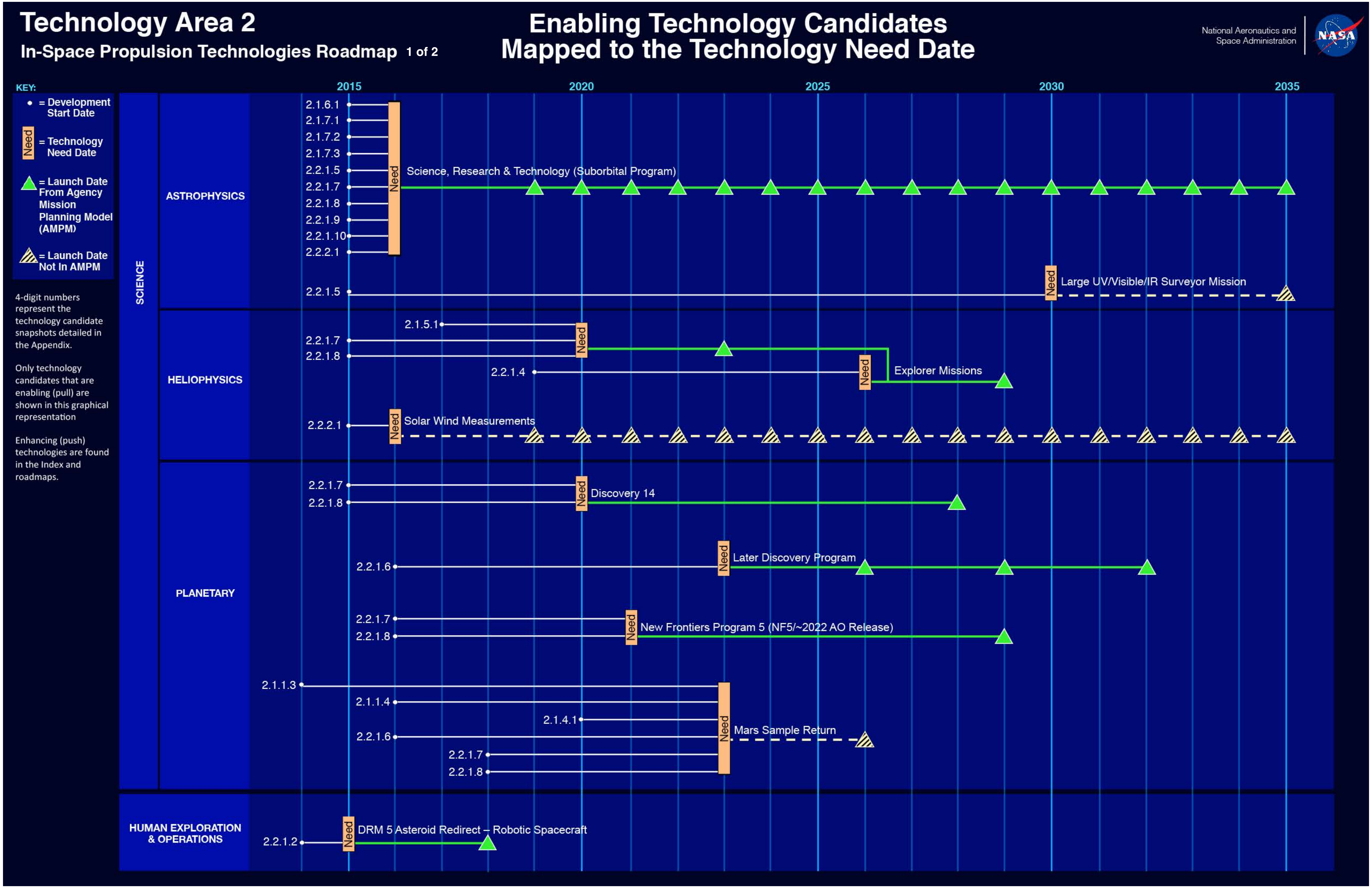


Figure 1. Technology Area Strategic Roadmap

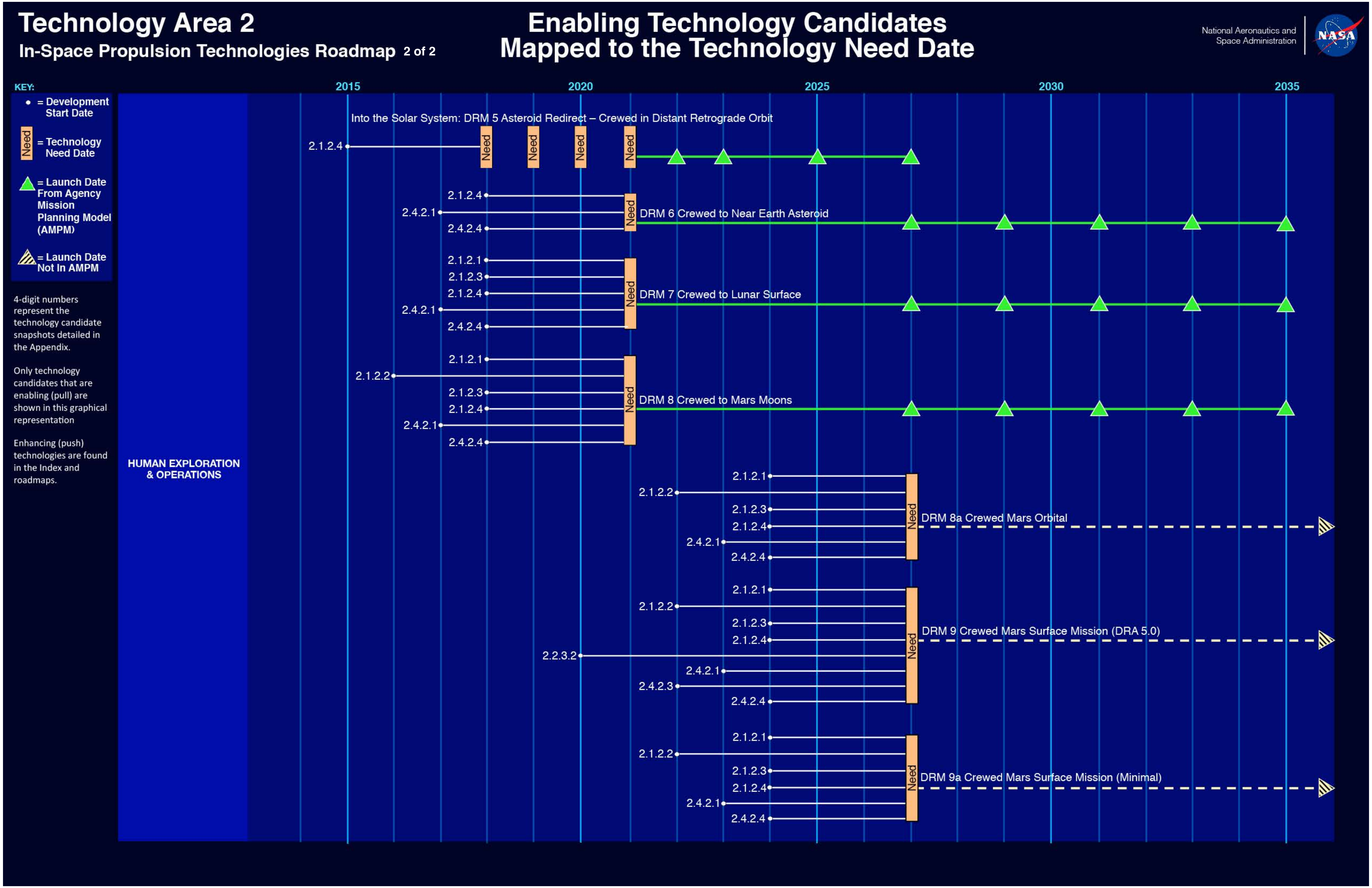


Figure 1. Technology Area Strategic Roadmap

Introduction

In-space propulsion begins where the launch vehicle upper stage leaves off, performing the functions of primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering. The main engines used in space provide the primary propulsive force for orbital transfer, planetary trajectories, and extra-planetary landing and ascent. The reaction control and orbital maneuvering systems provide the propulsive force for orbit maintenance, position control, station keeping, and spacecraft attitude control. This roadmap describes the portfolio of in-space propulsion technology candidates that could meet future NASA space science and exploration needs.

TA 2 **In-Space Propulsion Technologies**

2.1 Chemical Propulsion
- 2.1.1 Liquid Storable
- 2.1.2 Liquid Cryogenic
- 2.1.3 Gels
- 2.1.4 Solid
- 2.1.5 Hybrid
- 2.1.6 Cold Gas/Warm Gas
- 2.1.7 Micropropulsion

2.2 Non-Chemical Propulsion
- 2.2.1 Electric Propulsion
- 2.2.2 Solar and Drag Sail Propulsion
- 2.2.3 Thermal Propulsion
- 2.2.4 Tether Propulsion

2.3 Advanced (TRL <3) Propulsion Technologies
- 2.3.1 Beamed Energy Propulsion
- 2.3.2 Electric Sail Propulsion
- 2.3.3 Fusion Propulsion
- 2.3.4 High-Energy-Density Materials
- 2.3.5 Antimatter Propulsion
- 2.3.6 Advanced Fission
- 2.3.7 Breakthrough Propulsion

2.4 Supporting Technologies
- 2.4.1 Engine Health Monitoring and Safety
- 2.4.2 Propellant Storage and Transfer
- 2.4.3 Materials and Manufacturing Technologies
- 2.4.4 Heat Rejection
- 2.4.5 Power

Figure 2. Technology Area Breakdown Structure Technology Areas for In-Space Propulsion Technologies

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next twenty years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

The roadmap for this technology area is divided into four basic groups: 1) Chemical Propulsion, 2) Non-Chemical Propulsion, 3) Advanced Propulsion Technologies, and 4) Supporting Technologies. Figure 2 is a graphical representation of the In-Space Propulsion Technology Area Breakdown Structure (TABS). The TABS is divided into the four basic groups, based on the physics of the propulsion system and how it derives thrust, as well as its technical maturity. There may be credible in-space propulsion concepts not foreseen or captured in this document that might be beneficial to future mission applications. Care should be taken when implementing future development strategies to provide a conduit through which these concepts can be competitively engaged to encourage continued innovation.

2.1 Chemical Propulsion

Chemical Propulsion includes systems that operate through chemical reactions to heat and expand a propellant (or use a fluid dynamic expansion, as in a cold gas) to provide thrust. These technologies can be grouped into the following general categories:

- **2.1.1 Liquid Storable:** Propellants that remain stable over a range of pressures and temperatures and can be stored in a closed vessel for long periods of time.
- **2.1.2 Liquid Cryogenic:** Propellants that are liquefied gases at low temperatures. These systems provide high performance, but can present storage and handling challenges to prevent vaporization losses.
- **2.1.3 Gels:** Gelled and metallized fuels are a class of thixotropic (shear-thinning) fuels that improve the performance of rocket and air-breathing systems.
- **2.1.4 Solid:** Solid propellants are usually pre-mixed oxidizers and fuels that are then cast into a particular shape, so that when the surface is ignited the surface area burns at a predetermined and tailored burn rate to generate the thrust and duration required for the mission.
- **2.1.5 Hybrid:** Hybrid rockets utilize a solid fuel and liquid oxidizer. They are potentially safer and have a higher specific impulse (I_{sp}) than solid rockets. They are also less complex and cheaper than liquid rockets.
- **2.1.6 Cold Gas/Warm Gas:** Gas propulsion systems are typically used for small-delta-V rockets or when small total impulse is required.
- **2.1.7 Micropropulsion:** Chemical propulsion microthrusters are simply miniature versions of the larger thrusters described above. These miniature systems are used as propulsion systems for very small satellites or used as a form of precision control for both attitude and translation maneuvers.

It will be necessary to solve modeling challenges for chemical propulsion, such as predicting dynamic instability during combustion or the combined reaction physics and fluid dynamics for performance and thrust chamber cooling.

2.2 Non-Chemical Propulsion

Propulsion systems that use electrostatic, electromagnetic, field interactions, fission reactions, photon interactions, or externally supplied energy to accelerate a spacecraft are grouped together under Non-Chemical Propulsion. These technologies can be further grouped into the following categories:

- **2.2.1 Electric Propulsion:** Electric propulsion uses electrostatic and/or electromagnetic fields to interact with and accelerate a reaction mass (e.g., propellant) to generate thrust.
- **2.2.2 Solar and Drag Sail Propulsion:** Sail propulsion uses lightweight structures with a large surface area to produce thrust by reflecting solar photons (solar) or atmospheric molecules (drag), thereby transferring much of their momentum to the sail.

- **2.2.3 Thermal Propulsion:** Thermal propulsion systems use solar or fission energy to heat a mono-propellant for thermal expansion through a traditional nozzle.
- **2.2.4 Tether Propulsion:** Tethers are long, lightweight cables that 1) produce thrust through the Lorentz force by carrying electrical current and interacting with a planetary magnetosphere, or 2) by exchanging momentum between two tethered objects.

Non-chemical propulsion technologies require the enhancement and validation of complicated analytical tools, including electric propulsion device life models to shorten life qualification testing, electric propulsion plume models to evaluate spacecraft interactions, and complex reactor models to optimize the nuclear thermal propulsion (NTP) engine system.

2.3 Advanced (TRL < 3) Propulsion Technologies

Advanced Propulsion Technologies include technologies and physics concepts that are at Technology Readiness Level (TRL) 3 or below. These technologies can be grouped into the following general categories:

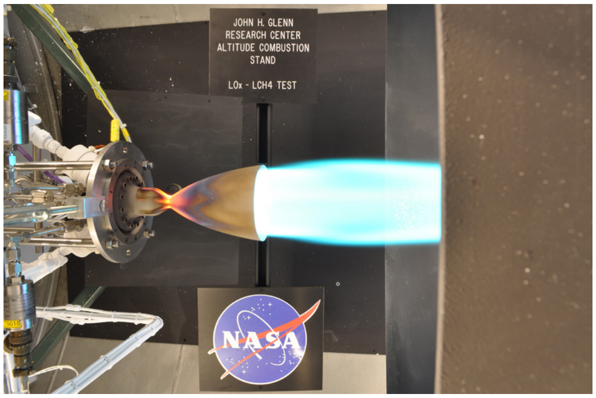
- **2.3.1 Beamed Energy Propulsion:** Beamed energy propulsion uses laser or microwave energy from a ground- or space-based energy source and beams it to an orbital vehicle, which uses it to heat a propellant or reflected photon momentum exchange.
- **2.3.2 Electric Sail Propulsion:** Long, lightweight, high-voltage wires (tens of kilometers (km)) that are kept in a high positive potential provide thrust in interplanetary space by repelling solar wind protons, thus deflecting their paths and extracting momentum from them.
- **2.3.3 Fusion Propulsion:** Fusion propulsion involves using fusion reactions to produce the energy required for spacecraft propulsion. This can be accomplished directly or indirectly by using the thermal/kinetic energy resulting from the fusion reactions to accelerate a propellant.
- **2.3.4 High-Energy-Density Materials:** These materials consist of atoms trapped in solid cryogens (neon, etc.). Atomic hydrogen, boron, and carbon fuels are very high-energy-density, free-radical propellants. Atomic hydrogen may deliver an I_{sp} of 600 to 1,500 seconds. There has been great progress in the improvement of atom storage density over the last several decades. Laboratory studies have demonstrated 0.2 and 2 weight percent atomic hydrogen in a solid hydrogen matrix. Atom storage at the 10 to 15 percent levels would produce an I_{sp} of 600 to 750 seconds.
- **2.3.5 Antimatter Propulsion:** Antimatter propulsion is based on conversion of a large percentage (up to ~75 percent) of fuel mass into propulsive energy by annihilating atomic particles with their antiparticles. Small quantities of antimatter can be used to trigger fission/fusion reactions.
- **2.3.6 Advanced Fission:** Advanced fission systems involve concepts that utilize fission-produced energy to achieve greater propulsion performance than solid-core NTP.
- **2.3.7 Breakthrough Propulsion:** Breakthrough propulsion is an area of technology development that seeks to explore and develop a deeper understanding of the nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomena, with the overall objective of developing advanced propulsion applications and systems that will revolutionize how NASA explores space.

2.4 Supporting Technologies

Supporting Technologies are pertinent technology areas that are strongly coupled to, but are not part of, in-space propulsion, such that focused development within these related areas will allow significant improvements in performance for some in-space propulsion technology areas. These technologies can be grouped into the following general categories:

- **2.4.1 Engine Health Monitoring and Safety:** Use of simulation and data processing to determine and mitigate operational, safety, and reliability risks and issues in the propulsion system. In general, the key metrics for health monitoring for in-space propulsion are reliability, weight, and cost.
- **2.4.2 Propellant Storage and Transfer:** Cryogenic Fluid Management (CFM) broadly describes the suite of technologies that can be used to enable the efficient in-space use of cryogens despite their propensity to absorb environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity, and the uncertainty of the position of the liquid-vapor interface when the propellants are not settled.
- **2.4.3 Materials and Manufacturing Technologies:** Structures and materials play a critical role in all in-space propulsion systems for both human and robotic missions. In some cases, material, structural, or manufacturing advances are required to enable propulsion technology advances. In other cases, the structural and material advances are enhancing, or can result in a significant propulsion system improvement of their own. In general, the key materials and manufacturing metrics for in-space propulsion are temperature capability, weight, and cost.
- **2.4.4 Heat Rejection:** Heat rejection is a key supporting capability for several in-space propulsion systems. Some examples include rejection of the waste heat generated due to inefficiencies in electric propulsion devices and rejection of the heat removed from a cryogenic propellant storage system by a cryocooler. In general, the key heat rejection systems metrics for in-space propulsion are cost, weight, operating temperature, and environmental durability (e.g., radiation, micrometeoroid and orbital debris (MMOD)).
- **2.4.5 Power:** Power systems play an integral role in all in-space propulsion systems for both human and robotic missions. In some cases, power is only required for basic functions of instrumentation and controls and technology advances are not required. In other cases, the propulsion energy of the technology is derived from electrical power generation, management, and distribution, and advances in power system technologies are therefore critical for advancing propulsion systems (e.g., high-power solar or nuclear electric propulsion). In general, the key power system metrics for in-space propulsion are cost, reliability, specific power, operating ranges (power and environmental), and maximum power generation.

TA 2.1: Chemical Propulsion



LOX Methane RCS testing

Chemical Propulsion involves the chemical reaction of propellants to provide kinetic energy to move or control a spacecraft. Chemical propulsion system functions include primary propulsion, reaction control, station keeping, precision pointing, and orbital maneuvering. The main engines provide the primary propulsive force for orbit transfer, planetary trajectories, and extra-planetary landing and ascent. The reaction control and orbital maneuvering systems provide the propulsive force for orbit maintenance, position control, station keeping, and spacecraft attitude control. With the exception of electric propulsion systems used for orbit positioning, station keeping commercial communications satellites and a handful of lunar and deep-space science missions, all of the rocket engines in use today are chemical rockets. That is, they obtain the energy needed to generate thrust by combining reactive chemicals to create a hot gas that is expanded to produce thrust. A significant limitation of chemical propulsion is that it has a relatively low I_{sp}.

Sub-Goals

Chemical propulsion systems have the most in-space flight heritage, and many aspects of the technology are well understood. The sub-goals of the chemical propulsion technology development are focused on improving existing systems particularly in the areas of performance, reliability, and safety.

Table 2. Summary of Level 2.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
2.0 In-Space Propulsion Technologies	Goals:	Enhance current missions and open up new mission opportunities through improvements in performance, manufacturability, durability, and cost; and development of new propulsion capabilities.
Level 2		
2.1 Chemical Propulsion	Sub-Goals:	Improve performance, reliability, and safety.
Level 3		
2.1.1 Liquid Storable	Objectives:	Improve key performance characteristics while maintaining or improving on component lifetime and reliability. Develop engines that operate on non-toxic storable propellants.
	Challenges:	None identified.
	Benefits:	Reduces cost and improves the overall efficiency of system operations.
2.1.2 Liquid Cryogenic	Objectives:	Develop reaction control and main propulsion systems that operate on liquid oxygen and liquid methane or liquid hydrogen.
	Challenges:	Preventing boil-off for long-duration missions. Development of a highly throttle-able propulsion system for precise control on landing and emergency abort procedures.
	Benefits:	Reduces vehicle complexity by eliminating the number of propellants required to complete the mission. Provides increased mission flexibility when used as part of a planetary exploration system that uses in-situ resources for propellant manufacturing.

Table 2. Summary of Level 2.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
2.1.3 Gels	Objectives:	Increase fuel density and I_{sp}.
	Challenges:	Cryogenic fluid management. Storage stability and combustion efficiency from gelling the fuels with aluminum particles.
	Benefits:	Increases fuel density and increases I_{sp}.
2.1.4 Solid	Objectives:	Improve performance, durability, and mass fraction. Develop electrically-started solid rocket systems that enable solid motor shutdown and restart capability.
	Challenges:	Long-term storage in space. Specific propellant formulation for a particular mission.
	Benefits:	Reduces cost and improves the overall safety and efficiency of the system.
2.1.5 Hybrid	Objectives:	Provide multiple motor restart capability with lower operational complexity than an all-liquid propulsion system.
	Challenges:	Long-term exposure to a space environment.
	Benefits:	Provide safer operations and higher I_{sp} propulsion to solid rockets and are simpler relative to storage, handling, and operation than bipropellant liquid systems.
2.1.6 Cold Gas/Warm Gas	Objectives:	Increase I_{sp}.
	Challenges:	None identified.
	Benefits:	Provides a compact gas propulsion system that generates a small delta-V or small total impulse to a spacecraft system. Increases the I_{sp}, which will also increase the mission delta-V and total impulse.
2.1.7 Micropropulsion	Objectives:	Develop compact and lightweight systems with high precision control capability.
	Challenges:	None identified.
	Benefits:	Provides precise attitude control and precision impulses.

TA 2.1.1 Liquid Storable

Liquid storable propellants remain stable over a range of pressures and temperatures. This type of propellant may be stored for long periods of time. Storable propellant systems are either in a bipropellant or monopropellant configuration. The most common storable propellants are nitrogen tetroxide (NTO) and monomethyl hydrazine (MMH). In a bipropellant system, the propellants are generally hypergolic, where ignition occurs instantaneously upon contact when mixed. This type of system is commonly used because it is reliable and eliminates the need for a separate ignition system. These bipropellant systems are more commonly found on larger main propulsion systems for orbit insertion, orbital maneuvering, or surface descent/ascent. In the monopropellant configuration, a propellant such as hydrazine is decomposed through a catalyst bed to create a high-temperature gas for thrust. These systems are used in spacecraft attitude and reaction control systems (RCS). While commonly used, the catalyst system has shown issues with life and cold-start capabilities. A significant drawback to the current storable systems is the toxicity of the propellant. The toxicity makes necessary specialized safety equipment, such as Self Contained Atmospheric Protective Ensemble (SCAPE) suits, as well as stringent safety procedures for handling and transportation.

Technical Capability Objectives and Challenges

This technology area is comprised of four types of liquid storable technologies, including monopropellants, bipropellants, high-energy propulsion, and high-energy oxidizers. The new technology-based systems look to improve key performance characteristics while maintaining or improving on component lifetime and reliability.

Monopropellant technologies require the development of non-toxic variants from 1 Newton to 500 Newton thrusters to achieve increased specific energy performance, along with improved safety and handling efficiency for use as reaction control thrusters that provide small accelerations to maintain or adjust the spacecraft attitude. The propellants could potentially also be used for spacecraft main propulsion.

Bipropellant technologies require the development of non-toxic variants from 220 Newton to 30,000 Newton engines to achieve I_{sp}, throttle capacity, lifetime, and reliability performance comparable to or increased from the state of the art (SOA), along with improved safety and handling efficiency for use as reaction control thrusters and orbital maneuvering engines.

High-Energy Propulsion uses an oxidizer and a fuel that together undergo combustion to generate thrust. One of the two propellants may be a cryogenic fluid and will also require spark ignition systems. Liquid oxygen/hydrazine (LO_2/N_2H_4) is a propellant option that has comparable performance to liquid oxygen/methane (LO_2/LCH_4). Higher thrust levels (greater than 100 pounds of thrust) are needed for Science Mission Directorate (SMD) missions.

High-Energy Oxidizers, such as fluorinated compounds, include chlorine trifluoride (ClF_3), chlorine pentafluoride (ClF_5), and oxygen difluoride (OF_2). These oxidizers have a long history of testing, with the most recent testing conducted in the 1980s. Stages for interceptors were created for flight testing using hydrazine/ClF_5. They offer much higher energy and rocket I_{sp} than Earth-storable nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) propellants.

Benefits of Technology

The handling of NTO and MMH requires stringent safety procedures, and even the smallest leak is considered extremely dangerous. To reduce the cost and improve the overall efficiency of system operations, a new class of non-toxic propellants is currently in development as a replacement for hydrazine. The new propellants (e.g., AF-M315 and LMP-103S) are examples of ionic liquids that are safer to handle and offer improved performance. However, these propellants do have some of the same challenges associated with catalysts and may require new materials for combustion components because of a higher combustion temperature.

Table 3. TA 2.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.1.1	Monopropellants	Monopropellant thrusters use a single Earth- and space-storable propellant decomposed to generate high-temperature gas for thrust.
2.1.1.2	Bipropellants	Bipropellant thrusters use Earth- and space-storable propellant to generate a chemical reaction, typically hypergolic, to produce high-temperature gas that is expanded to generate thrust.
2.1.1.3	High Energy Propellants	Higher energy propellant combinations can increase rocket engine performance and increase vehicle payload mass. An example is liquid oxygen/hydrazine (LO_2/N_2H_4), with 340 to 350 seconds of I_{sp}.
2.1.1.4	High Energy Oxidizers	Fluorinated compounds can increase rocket I_{sp} by 10 to 70 seconds. An example is fluorine/hydrazine (F_2/N_2H_4) with 360 to 370 seconds of I_{sp}.

TA 2.1.2 Liquid Cryogenic

Currently liquid cryogenic propellants used for in-space transfer stages use liquid oxygen (LO_2 or LOX) and liquid hydrogen (LH_2). Liquid cryogenic propellants are gases that are liquid at very low temperature. For example, the boiling point for LO_2 is -297.3 degrees Fahrenheit (° F) and for LH_2 it is -423.2° F. Thrust ranges for in-space stages using these propellants have been developed up to 50,000 pounds-force (lbf). Recent developments have focused on large in-space transfer stages with thrust levels up to 25,000 lbf. Liquid hydrogen is also used for high-thrust nuclear thermal rockets, which are an option for future Mars missions. Cryogenic propellants are used because of their high performance. However, storage and transfer of cryogenic propellants can be a challenge; in particular, preventing boil-off for long-duration missions is difficult. Due to the difficulties with maintaining the propellant hydrogen as a liquid and the corresponding low storage density of liquid hydrogen, investigations have been conducted into using liquid methane (LCH_4) as an alternate fuel. The properties of methane, particularly its boiling point of -263.2° F, are closer to those of liquid oxygen, so using methane might provide system simplifications. Methane is a potential propellant option for reaction control and ascent/descent propulsion systems. Another potential advantage of methane is that it can be produced in-situ from resources on Mars. One objective for the use of cryogenic reaction control is to integrate the feed system with the main propulsion system. The combined system presents a number of challenges with storage and propellant quality on demand, particularly for pulsing reaction control systems. For ascent/descent propulsion, both pump-fed and pressure-fed systems are options. A key challenge for both hydrogen and methane propulsion is the development of a highly throttle-able propulsion system for precise control on landing and emergency abort procedures.

Technical Capability Objectives and Challenges

The development of liquid oxygen-liquid methane propulsion systems provides NASA with enhanced capacities for planetary descent, planetary ascent, orbit transfer, and reaction control propulsion systems. Cryogenic propellants are well suited for missions that require a high I_{sp} and wide throttling range.

For ascent/descent propulsion, both pump-fed and pressure-fed systems are options. Target performance levels for main propulsion are at an I_{sp} of at least 355 seconds with an operational life of more than 300 seconds. Another key challenge for both hydrogen and methane propulsion is the development of a highly throttle-able (10 percent of full thrust) propulsion system for precise control on landing and emergency abort procedures. For reaction control systems, the objective is to develop propulsion systems with up to 100 lbf thrust and over 300 seconds of I_{sp} with ignition reliability equal to that of hypergolic propellants and rapid pulse rates. Methane-based propulsion systems also could be used as part of a planetary exploration system that uses in-situ resources for propellant manufacturing.


LOX Methane Main Engine Test

Benefits of Technology

The use of cryogenic propulsion systems will allow for greater mass to and from the surface over SOA propulsion systems and alleviates extravehicular activity (EVA) concerns for propellant exposure, along with simplifying loading and testing operations. Beyond improved performance, a cryogenic reaction control system can be integrated as part of a single feed system with the main propulsion system. Additionally, the main and reaction control feed systems can be integrated with the power, environmental control, and life support systems, thereby reducing the overall vehicle mass. The combined system will reduce vehicle complexity by eliminating the need for separate systems with multiple propellants required to complete the mission. Methane-based propulsion systems could also provide increased mission flexibility when used as part of a planetary exploration system that uses in-situ resources for propellant manufacturing.

Table 4. TA 2.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.2.1	Liquid Oxygen (LO_2), Methane (CH_4) Pressure-Fed Main Engine	Pressure-fed rocket engines for primary propulsion that use liquid methane as the fuel.
2.1.2.2	Liquid Oxygen (LO_2), Methane (CH_4) Pump-Fed Main Engine	Pump-fed rocket engines for primary propulsion that use liquid methane as the fuel.
2.1.2.3	Liquid Oxygen (LO_2), Methane (CH_4) Reaction and Attitude Control Engine	Rocket engines for reaction control that use liquid methane as the fuel.
2.1.2.4	Liquid Oxygen (LO_2), Liquid Hydrogen (LH_2) Reaction and Attitude Control Engine	Rocket engines for reaction and attitude control that use liquid hydrogen as the fuel. Thruster could also be used as primary propulsion for science missions.

TA 2.1.3 Gels

Gelled and metallized fuels are a class of thixotropic (shear-thinning) fuels that improve the performance of rocket systems in several ways: increased rocket I_{sp}, increased fuel density, reduced spill radius in an accidental spill, lower volatility during accidental low-pressure propellant fires, reduced fuel sloshing, and lower leak potential from damaged fuel tanks (due to higher propellant viscosity). For these reasons, there is a demand for gelled fuels.

NASA has studied gelled fuels analytically and experimentally for lunar and Mars missions, upper stages, interplanetary robotic missions, and launch vehicle applications. Increased fuel density and increased engine I_{sp} are the primary benefits.

Technical Capability Objectives and Challenges

Gelled cryogenic propellants have only been tested in laboratory experiments and have not yet flown in a space-representative environment. Boil-off and the corresponding shift in propellant-loading are potential issues. Cryogenic fluid management issues must also be addressed. Storable NTO/MMH/Aluminum, O_2/Rocket Propellant (RP)-1/Aluminum, and Cryogenic O_2/H_2/Aluminum are the primary candidates for gel propellants. The primary challenges arise from gelling the fuels with aluminum particles, including storage stability and combustion efficiency.

Benefits of Technology

Increased fuel density and increased I_{sp} are primary benefits. Nanometer-sized particles are added to the fuel to deliver higher-density and higher rocket I_{sp}. These increases lead to increased space vehicle payload mass. Metallized gelled propulsion can increase NTO/MMH I_{sp} by 25 seconds, and O_2/H_2 I_{sp} by 5 to 10 seconds. With O_2/H_2/Aluminum, an additional 22 to 33 percent payload mass increase on human Mars missions is enabled. For upper stages, a 15 to 20 percent increase in injected payload mass is enabled for NTO/MMH/Aluminum.

Table 5. TA 2.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.3.1	Gelled and Metalized-Gelled Propellants	Micrometer/nanometer-sized particles are added to the fuel to deliver higher density and higher rocket I_{sp}.

TA 2.1.4 Solid

Solid propellants usually comprise pre-mixed oxidizer and fuel. The mix is cast so that the surface area burns at a predetermined and tailored burn rate when ignited. The burn rate generates the thrust and duration required for the mission. For solid propellants, I_{sp} values are normally less than 300 seconds. For space-based solids, hydroxyl-terminated polybutadiene (HTPB) propellant has been used exclusively in apogee kick-motors and upper stages. Thrust vectoring is controlled by gimballing or gaseous/liquid injection.

Technical Capability Objectives and Challenges

There are four objectives related to advancing solid rocket propulsion for in-space applications: 1) develop and hot-fire test formulations with nanoparticles or other additives included in the solid propellant mix to increase propellant energy density and propellant structural integrity; 2) develop and qualify propellant with improved durability to withstand long-term exposure to a space environment; 3) improve vehicle mass fraction via enhancements to vehicle structural and system component technology (e.g., composite motor casing, lightweight nozzle, and consumable igniter); and 4) complete development of electrically-started solids technology that enables solid motor shutdown and restart capability for solid motors in the millinewton thrust range.

The most significant technology issue and challenge is long-term storage in space, which is presently unproven. Also, a specific propellant formulation has to be identified for a particular mission.

Benefits of Technology

Solid rockets are relatively simple to operate and have a high-density I_{sp}. The pre-mixed oxidizer and fuel can be cast into a particular shape to predetermine and tailor burn rates to generate the thrust and duration required for a mission. Electrically-actuated solids have thrust levels in millinewtons, which make them applicable to nanosats as attitude-control thrusters.

Table 6. TA 2.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.4.1	Solid Propulsion for Deep Space	Source of impulse for spacecraft. A rocket motor that uses solid propellants (fuel and oxidizer).

TA 2.1.5 Hybrid

Hybrid rockets utilize a solid fuel and liquid oxidizer. They are potentially safer and have a higher I_{sp} than solid-propellant rockets, and they are less complex and less expensive than liquid rockets. Hybrid rockets are generally larger in volume than solid rockets due to the lower density of their propellants. Hybrid fuel regression rates are typically much less than that of solid propellants. Hybrid motors have been demonstrated at the 250-kilo pounds-force (klbf) thrust level in ground testing. Recent developments in hybrid technology have resulted in significant progress, reducing technology risk, with long-burn-duration firings at the 20 klbf thrust level for an upper stage application.

Technical Capability Objectives and Challenges

In-space use of hybrid propulsion technology has not been demonstrated. The objective of developing hybrid propulsion technology is to create an alternative in-space propulsion technology, one that provides multiple motor restart capability with lower operational complexity than an all-liquid propulsion system, and a substantially reduced safety risk relative to solid rocket propulsion. More specifically, the objective is to identify, develop, and hot-fire test fuel formulations that increase propellant energy density and structure integrity relative to SOA capability and develop and demonstrate that the propellant will withstand long-term exposure to a space environment.

Benefits of Technology

Hybrid rockets utilize a solid fuel and liquid oxidizer. They are potentially safer and have a higher I_{sp} than solid rockets and are simpler relative to storage, handling, and operation than bipropellant liquid systems. Hybrids produce non-toxic exhaust products. Explosive mixtures that can occur in liquid or solid rockets are less likely in hybrids.

Table 7. TA 2.1.5 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.5.1	Hybrid Propulsion for Space	A rocket motor that uses propellant in two different states of matter: one solid and the other either a liquid or gas.

TA 2.1.6 Cold Gas/Warm Gas

Cold gas systems have been flying in space since the 1950s, with thrust levels from fractions of a pound to tens of pounds. Warm gas systems have been used in flight systems for pressurization but not for main propulsion. The principal advantage of using the warm gas version of a cold-gas system is that it requires approximately half the propellant storage tank volume. Gas propulsion systems are typically used for small delta-V rockets or when small total impulse is required. These systems are generally inexpensive and very reliable, and inert gases are inherently non-toxic. Most of the residual risk lies with the high-pressure storage tanks, although good design provides ample margin for safety.

Technical Capability Objectives and Challenges

The technical capability objective is to mature warm-gas integrated propulsion systems toward a flight status. The advantage of warm gas over cold gas is that it requires a smaller tank size, and it increases I_{sp} to approximately 135 seconds. This will yield higher mission delta-V for a particular application.

Benefits of Technology

A cold or warm gas system provides a compact gas propulsion system that can provide small delta-V or small total impulse to a spacecraft system. Cold gas is currently flown in small satellites, upper stages, and is also used in human space exploration EVAs. Switching to a warm gas system will increase the I_{sp}, which will also increase the mission delta-V and total impulse.

Table 8. TA 2.1.6 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.6.1	Cold Gas/Warm Gas	Gas propulsion systems are typically used for small delta-V or when small total impulse is required; for example, attitude control of small spacecraft.

TA 2.1.7 Micropropulsion

There are many options that are flight ready for all categories of micropropulsion, ranging from about 0.1 Newton for cold gas and 1.07 Newton for hydrazine thrusters to 170 Newton for solid motor options. Micro-hydrazine thrusters are used to produce low thrust levels and minimum-impulse burns for reaction control systems. Solid motors are used to provide precision impulse for deployments, attitude changes, spin up and spin down, and more. Cold or warm gas propulsion systems are used for precise attitude control and precision-impulse bits.

Technical Capability Objectives and Challenges

Monopropellant microthrusters require the development of small catalyzer beds, small high-speed flow control valves, thermal control techniques, and non-toxic alternative propellants. There are solid-motor microthruster design candidates that have been developed above TRL 6. There are flight-ready forms of cold gas micropropulsion systems, so there are very few technical challenges with cold gas or warm gas systems. Some work has been done with systems that use liquefied gas and microelectromechanical systems (MEMS)-based thrusters for CubeSat applications. One potential driver for micropropulsion is the precision propulsion capability required for the formation flying of multiple spacecraft in a distributed-aperture sensor system. Spacecraft formation flying plays a critical role in enabling distributed apertures that synthesize a single "sensor" over multiple spacecraft. For more information about spacecraft formation flying requirements and distributed-aperture sensor systems refer to the TA 8 Science Instruments, Observatories, and Sensor Systems roadmap.

Benefits of Technology

Micropropulsion systems provide precise attitude control and precision impulses and enable broader capability from small spacecraft, including space environment observations with swarms of small spacecraft that are precisely located and positioned across large distances.

Table 9. TA 2.1.7 Technology Candidates – not in priority order

TA	Technology Name	Description
2.1.7.1	Solids	Solid motor microthrusters are miniature versions of large solid booster rockets.
2.1.7.2	Cold Gas/Warm Gas	Micropropulsion cold/warm gas thrusters are miniature versions of devices described earlier.
2.1.7.3	Monopropellant	Microthrusters using monopropellants are miniaturized versions of standard rocket engines that produce low thrust levels and minimum impulse bits for reaction control systems.

TA 2.2: Non-Chemical Propulsion

Non-Chemical Propulsion provides thrust without combustion and chemical reactions. Example technologies include: systems that accelerate reaction mass electrostatically or electromagnetically (electric propulsion), systems that energize propellant thermally (solar or nuclear thermal propulsion), and those that interact with the space environment to obtain thrust (solar sail and tether propulsion).

There are a number of propulsion options discussed in this section and the tables, all of which offer efficient propulsion system solutions to the mission planner in the form of high I_{sp} (in some cases using no propellant). In the case of thermal propulsion (e.g., NTP), these solutions can also provide moderate to high thrust along with the efficient use of propellant. The NTP category has seen some active work to mature reactor fuel elements. Within the area of Hall thrusters, there is some mission pull to help mature thrusters in the 10 to 15 kilowatt (kW) range. Ion engines have seen considerable progress in the lab with the 7.2 kW NASA Evolutionary Xenon Thruster (NEXT) demonstrating extremely long life, and some work with the higher power Nuclear Electric Xenon Ion System (NEXIS). The NEXT thruster should be matured to flight for possible inclusion on a science mission application. Solar sail technology has some mission plans in work to support small-scale flight opportunities (e.g., CubeSats).

Sub-Goals

The sub-goal for electric propulsion is to continue to mature higher-power Hall thrusters and ion engines for flight, mature the electromagnetic technologies in the lab, and continue to explore miniaturization of some of these solutions with an eye towards CubeSats and precision-formation flying. The sub-goal for solar and drag sail propulsion is to continue to fly small classes of sails, improve the manufacturing capabilities so that large and lightweight sails can be produced, and work out robust on-orbit deployment strategies for these large sails. Solar thermal propulsion (STP) sub-goals include developing high-temperature materials' optical-quality and inflatable concentrators. NTP should continue to see maturation of the fuel element materials and manufacture process, cladding, and possibly work towards integrated testing if ground test facilities can be availed. In the area of tether propulsion, the next step should be a system-level validation of electrodynamic tethers in space.

Table 10. Summary of Level 2.2 Sub-Goals, Objectives, Challenges, and Benefits

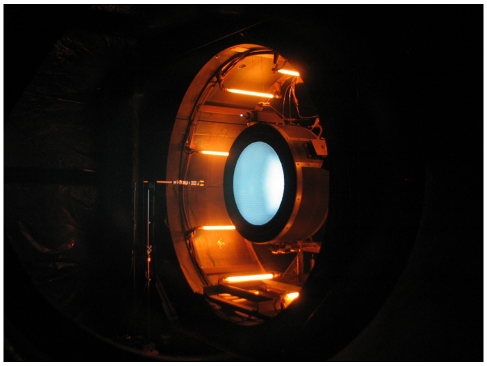
Level 1		
2.0 In-Space Propulsion Technologies	Goals:	Enhance current missions and open up new mission opportunities through improvements in performance, manufacturability, durability, and cost; and development of new propulsion capabilities.
Level 2		
2.2 Non-Chemical Propulsion	Sub-Goals:	Improve performance and lifetime. Enable mission opportunities with efficient alternatives to chemical propulsion.
Level 3		
2.2.1 Electric Propulsion	Objectives:	Increase performance and lifetime.
	Challenges:	Long thruster operational lifetime. Manufacturing of miniaturized propulsion concepts.
	Benefits:	Provides high-I_{sp} in-space propulsion. Reduces propellant mass for a given mission, enables longer-duration missions, allows for missions with multiple destinations, and provides mission flexibility for unforeseen in-flight anomalies.

Table 10. Summary of Level 2.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

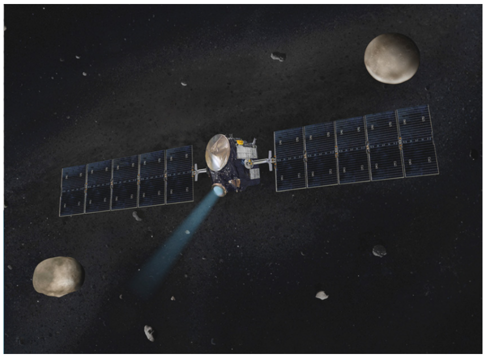
Level 3		
2.2.2 Solar and Drag Sail Propulsion	Objectives:	Develop larger and more capable solar and drag sail systems.
	Challenges:	Manufacturing, packaging, deployment, guidance, navigation, and control for large sails.
	Benefits:	Provides sustained observation of the Earth's polar regions, persistent station keeping at sub-Lagrange Point 1 (sub-L1) (Earth-Sun) for space weather monitoring, enhanced access to the Sun's polar regions, and rapid transit to the heliopause and beyond (> 250 astronomical units (AU)). Provides inexpensive propulsion option for deep space CubeSats and small satellites.
2.2.3 Thermal Propulsion	Objectives:	Increase I_{sp} of solar thermal propulsion. Develop a nuclear thermal propulsion system.
	Challenges:	Extremely high temperatures required to provide high I_{sp} and reduce the large volume required for the LH_2 propellant for an STP launch. NTP reactor fuel design that achieves higher temperature, minimum erosion, and fission product release and uses reduced quantities of enriched uranium. Special NTP ground test concept that demonstrates full system qualifications and meets government environmental regulations.
	Benefits:	STP provides larger-mass payloads than chemical propulsion for a single launch of small to medium payloads. NTP provides shortest trip times for human missions to Mars and other destinations due to NTP's high thrust and high I_{sp}.
2.2.4 Tether Propulsion	Objectives:	Develop long tethers with long life. Develop high-fidelity system-level models.
	Challenges:	Long-lived, micrometeoroid and debris damage-resistant tethers. Tether health-monitoring technologies.
	Benefits:	Provides very high delta-V for small robotic spacecraft in low-Earth orbit (LEO) and any planet with a magnetosphere to allow altitude and inclination change, end-of-life disposal, and nearly-indefinite station keeping without the use of propellant (electrodynamic). Provides reusable, high-thrust, high I_{sp} (equivalent) thrust to interplanetary or LEO-to-geosynchronous orbit transportation (momentum exchange).

TA 2.2.1 Electric Propulsion

The area of electric propulsion includes a diverse group of technology candidates. Resistojets and arcjets are two types of electrothermal solutions that are currently used extensively on communications satellites in the 50 to 2,000 watt range, with technology work exploring very small and very large solutions. Ion engines and Hall thrusters are another category of electric propulsion that uses electrostatic fields to ionize and accelerate a propellant. Both technologies are also used extensively in the communications satellite sector. Their flight power ranges are in the hundreds of watts to several kilowatts, and there are efforts to increase the power of Hall thrusters to over 10 kW for a flight application related to human exploration. The electromagnetic category includes the pulsed inductive thruster and the magnetoplasmadynamic (MPD) thruster. This class of thruster interacts with a reaction mass using electromagnetic fields and, although none of these systems are currently in use in space, they are typically envisioned to be high-power, starting in the 50 to 100 kW range. This higher-power category will be pertinent to human space exploration missions beyond LEO, and for rapid-transit science missions to the



NEXT PM1R During Thermal Vacuum Test

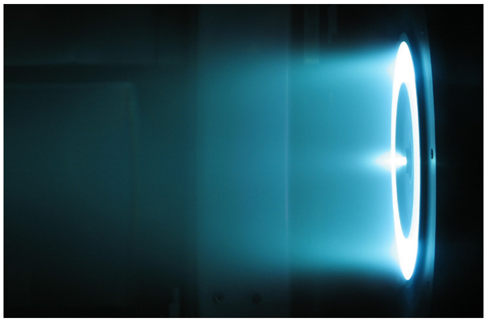


Dawn Spacecraft with Three NSTAR Gridded Ion Thrusters

outer solar system and deep space destinations. Lastly, miniaturization of a number of electric propulsion solutions is also an active area of technology development spanning down to the ability to impart forces that are measured in micronewtons.

Technical Capability Objectives and Challenges

In all forms of electric propulsion that feature low thrust and high I_{sp}, the central challenge is attaining the capability for a long thruster operational lifetime. In the area of gridded ion thrusters, there is some focus on increasing the power from the 7 kW level to higher than 20 kW while maintaining an I_{sp} of at least 4,000 seconds. In the Hall thruster category, there is emphasis on maturing a 10 to 15 kW class thruster for use with near-term human exploration missions, while continuing to explore and mature single thrusters in the 50 to 100 kW range, and nested Hall thrusters that exceed the 100 kW range. A 50 kW solar electric propulsion system is being developed as well as magnetically-shielded Hall thrusters for the Asteroid Redirect Mission. There are several electromagnetic propulsion concepts that continue to need maturation and development towards a goal of single-engine power levels of around 100 kilowatts with the ability to scale to over a megawatt (MW). Also, miniaturization of some of the electric propulsion concepts for emerging mission applications, such as CubeSat primary propulsion, highly accurate formation flying, and precision pointing for observatories has introduced some manufacturing challenges not previously experienced.



Hall Thruster (H6) Firing

Benefits of Technology

Electric propulsion provides high-I_{sp} in-space propulsion. It can significantly reduce propellant mass for a given mission, enable longer-duration missions, allow for missions with multiple destinations, and provide greater mission flexibility for launch delays and unforeseen in-flight anomalies.

Table 11. TA 2.2.1 Technology Candidates – not in priority order

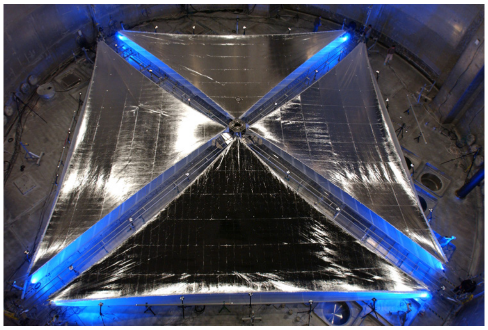
TA	Technology Name	Description
2.2.1.1	Ion Thrusters	Ion thrusters are electrostatic thrusters that use a variety of plasma generation techniques to ionize a large fraction of propellant. High voltage grids then extract the ions from the plasma and electrostaticly accelerate them to high velocity at voltages up to and exceeding 10 kV.
2.2.1.2	Hall Thrusters	Hall thrusters are electrostatic thrusters that utilize a cross-field discharge described by the Hall effect to generate and accelerate the plasma.
2.2.1.3	Pulsed Inductive Thruster	Pulsed electrode-less electric thruster that can operate on multiple propellants and that can be scaled to higher power by increasing the repetition rate.
2.2.1.4	Magnetoplasmadynamic (MPD) Thruster	Provides thrust by the interaction of high currents with either applied magnetic fields or a self-induced magnetic field to accelerate ionized propellant.
2.2.1.5	Electrospray Propulsion	Provides thrust using a conductive fluid and electrostatic fields to extract and accelerate charged droplets, clusters of molecules, or individual molecules or ions.
2.2.1.6	Wave Drive Thrusters	Wave-driven concepts like the wave-driven helicon and Ponderomotive thrusters. For example, the helicon concept provides thrust by forming plasmas with radio frequency (RF) discharge in an axial magnetic field to develop a helicon wave.
2.2.1.7	Miniature Hall Thruster	Hall thrusters are electrostatic thrusters that use a cross-field discharge described by the Hall effect to generate and accelerate the plasma.

Table 11. TA 2.2.1 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
2.2.1.8	Miniature Ion Thruster	Provide thrust by a variety of plasma generation techniques to ionize a large fraction of the propellant. High-voltage grids then extract the ions from the plasma and electrostaticly accelerate them to high velocity at voltages up to and exceeding 10 kV.
2.2.1.9	Resistojets	Resistojets use an electrically-heated element in contact with the propellant to increase the enthalpy prior to expansion through a nozzle.
2.2.1.10	Arcjets	Arcjets use an electric arc to heat the propellant prior to expansion through a nozzle.
2.2.1.11	Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	VASIMR is a high-power radio frequency driven plasma thruster capable of I_{sp}/thrust modulation at constant input power scalable over a broad range of power levels using efficient power processing units (PPUs) based on existing commercial radio broadcast technology.

TA 2.2.2 Solar and Drag Sail Propulsion

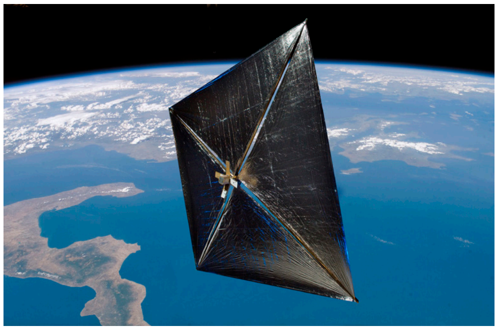
Solar sail propulsion technology is advancing for application to small spacecraft, from CubeSats to Explorer-class robotic missions. CubeSat solar sails have flown or will be flying soon. Larger sails with application to Explorer-class missions have been flown by a foreign space agency. To implement more ambitious missions, the capability to manufacture and deploy larger sails (1,200 m^2 to 90,000 m^2) must be developed and demonstrated in space.


Solar Sail

Technical Capability Objectives and Challenges

Solar sails derive propulsion by reflecting sunlight from a large, mirror-like sail made of a lightweight, reflective material. The continuous sunlight pressure provides efficient primary propulsion, without expending propellant or any other consumable, allowing for very high delta-V maneuvers and long-duration, deep-space exploration. Several missions and mission classes will be enabled by solar sail technology, requiring ever larger and more capable solar sail systems. First-generation sails require delta-V sufficient to create a long-life (10 years or more) artificial sub-Lagrange Point 1 (L1) that allows a spacecraft to station keep along the Sun/Earth line. Second-generation sails require delta-V sufficient to place a long-life (10 years or more) spacecraft in a heliocentric orbit with semi-major axis of 0.48 AU at an inclination of 75 degrees or higher. Third-generation sails require delta-V sufficient to enable a Voyager-class spacecraft to reach 250 AU within 20 years of launch. These requirements can be met by sails less than 3 microns thick with surface areas of 1,600 m^2, 22,500 m^2, and 90,000 m^2, respectively. The challenges are all related to the scale of the sails required – manufacturing, packaging, deployment, guidance, navigation, and control.

Drag sails provide thrust by changing the ballistic coefficient of a spacecraft, thereby increasing atmospheric drag. Drag sails may provide low-mass end-of-life propulsion for spacecraft deorbit. End-of-life drag sails will require that the spacecraft burn up upon reentry or be supplemented with a high-thrust system allowing for precision reentry targeting.


Drag Sail Propulsion

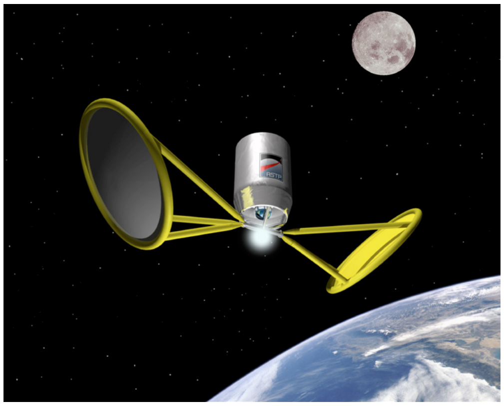
Benefits of Technology

Solar sails allow for sustained observation of the Earth's polar regions, persistent station keeping at Sub-L1 (Earth-Sun) for space weather monitoring, enhanced access to the Sun's polar regions, and rapid transit to the heliopause and beyond (> 250 AU). Small-scale solar sails also offer an inexpensive propulsion option for deep space CubeSats and small satellites. Drag sails provide a low-mass, low-cost deorbit capability for LEO spacecraft.

Table 12. TA 2.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
2.2.2.1	Solar Sail Propulsion	Solar sails provide thrust by reflecting light, using no propellant to provide thrust.
2.2.2.2	Drag Sail Propulsion	Drag sails provide thrust by changing the ballistic coefficient of a spacecraft, increasing atmospheric drag. Drag enhancement systems can assist in the end-of life disposal of a spacecraft.

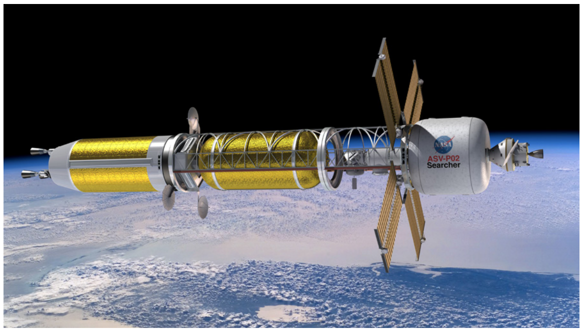
TA 2.2.3 Thermal Propulsion


Solar Thermal Propulsion

Thermal propulsion systems use other energy sources besides combustion (e.g., solar and nuclear fission) to heat the propellant via a heat exchanger and allow thermal expansion of the propellant through a traditional nozzle. The high I_{sp} requires extremely high-temperature materials, material compatibility with the propellant, and acceptable mission endurance. STP heats propellant from concentrated sunlight inside an absorber cavity and provides less than 5 lbf of thrust. In the 1990s, STP subsystems were developed with a variety of thruster concepts, propellant options, and materials. The greatest challenge was the large volume required for the LH_2 propellant. NTP uses a traditional solid core fission reactor in the thrust chamber to heat large quantities of propellant and provides tens to hundreds of klbf of thrust. A NASA program in the 1960s and 1970s developed the concept to a prototype flight design and tested engines ranging from 25 to 250 klbf. Current NTP efforts aim to increase the engine performance and reduce the thrust level for better affordability and broader mission utilization. Alternative solid core configurations have been considered. One prominent option is the pebble/particle bed reactor where the fuel is contained in pebbles that sit on a fluidized bed. Other core configurations include twisted carbide, grooved ring fuel element, wire core, and foam core.

Technical Capability Objectives and Challenges

STP has low thrust of approximately 2 to 4 lbf, but can provide high-I_{sp} greater than 900 seconds using hydrogen as the propellant. The primary challenge currently impeding STP development is the volume required by LH_2 for a single launch mission. An I_{sp} of 1,200 seconds would significantly reduce the required volume of LH_2, but also requires the use of extremely high-temperature carbide materials for the propellant heat exchanger.


Nuclear Thermal Propulsion Concept Vehicle

NTP provides a high thrust of approximately 25,000 lbf and high I_{sp} greater than 900 seconds using hydrogen as the propellant. NTP was identified as a leading option for Mars Design Reference Architecture 5.0. Challenges include a reactor fuel design that achieves higher temperature, minimum erosion, and fission product release and uses reduced quantities of enriched uranium than was developed for past programs. Affordable NTP development also requires a special ground test concept that demonstrates full system qualifications and meets current federal environmental regulations. Either of these challenges could take significant time to resolve.

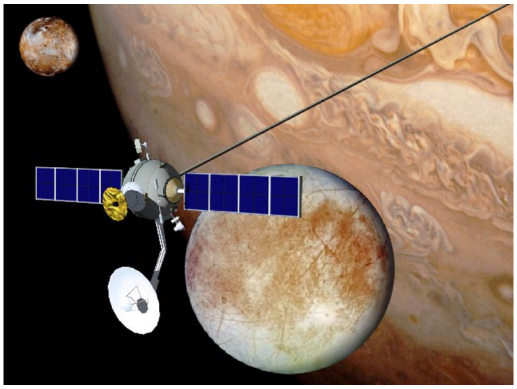
Benefits of Technology

STP can allow larger-mass payloads with slightly longer trip times than chemical propulsion for a single launch of small to medium payloads. NTP's high thrust and high I_{sp} can provide the shortest trip times for human missions to Mars and other destinations.

Table 13. TA 2.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
2.2.3.1	Solar Thermal Propulsion (STP)	Sunlight is captured with a large area concentrator and focused inside an absorber cavity to heat material to extremely high temperatures. The heat is transferred to the propellant and provides high I_{sp} at low thrust.
2.2.3.2	Nuclear Thermal Propulsion (NTP)	Solid core NTP engines use a fission reactor in the thrust chamber to heat large mass flow of propellant to extremely high temperatures for high I_{sp} at high thrust.

TA 2.2.4 Tether Propulsion



Electrodynamic Tether Propulsion

Tether propulsion uses a long cable, up to 100 kilometers, to generate thrust without the use of a propellant. Electrodynamic tether thrusters work by virtue of the force a magnetic field exerts on a wire carrying an electrical current (Lorentz Force). An electrodynamic tether thruster uses an electrical current flowing in the orbiting wire (the tether) so that the Earth's magnetic field accelerates it, and consequently, the payload attached to it. A spacecraft with an electrodynamic tether can expend electrical energy to boost its orbit (positive delta-V) or generate electrical energy by lowering its orbit (negative delta-V). The momentum exchange tether is a rotating system with a mass on both ends connected by the tether. While the tether system rotates, the objects on either end of the tether will experience continuous acceleration; the magnitude of the acceleration depends on the length of the tether and the rotation rate. Momentum exchange occurs when an end body is released during the rotation, providing one end mass with a positive delta-V and the other receiving a negative delta-V.

The technology to enable propellant-less electrodynamic tether propulsion in LEO advanced rapidly through the early 2000s. Many of the subsystems required are mature, at TRL 6 or higher, though development of long-lived, micrometeoroid and debris damage-resistant tethers and tether health monitoring technologies are still needed. The technology requires a system-level validation in space. Momentum-exchange tether propulsion is less mature, requiring additional capabilities in modeling of extremely large, flexible structures in space, orbital debris avoidance, and spacecraft catch and release mechanisms.

Momentum Exchange Tether Propulsion

Technical Capability Objectives and Challenges

Electrodynamic tethers require long tether systems (from hundreds of meters to 100 kilometers), long-life tethers (more than 1 year) and high-power systems (1-2 kW). Validation of high current-collection models is needed. Most of the required subsystem technologies have been demonstrated in space and a systems-level flight test is required to demonstrate the systems-level performance of the technology and to prevent the TRL from slipping backward as the core expertise gained thus far undergoes attrition.

Momentum exchange tethers require long tether systems (multi-kilometer); long-life tether systems (more than 1 year); high-fidelity models of tether dynamics during all mission aspects (deployment, orbital operation and propagation, catch and release); as well as subsystem- and system-level validation in space.

Benefits of Technology

Electrodynamic tethers provide very high delta-V for small robotic spacecraft in LEO and any planet with a magnetosphere to allow altitude and inclination change, end-of-life disposal, and nearly-indefinite station keeping without the use of propellant. Momentum exchange tethers provide reusable, high-thrust, high I_{sp} (equivalent) thrust to interplanetary or LEO-to-geosynchronous orbit transportation.

Table 14. TA 2.2.4 Technology Candidates – not in priority order

TA	Technology Name	Description
2.2.4.1	Electrodynamic Tether Propulsion	Electrodynamic tethers provide thrust by using a current-carrying wire to interact with a planetary magnetosphere via the Lorentz force.
2.2.4.2	Momentum Exchange Tether Propulsion	Rotating tethers create a controlled force on the end-masses of the system due to centrifugal acceleration. While the tether system rotates, the objects on either end of the tether will experience continuous acceleration; the magnitude of the acceleration depends on the length of the tether and the rotation rate. Momentum exchange occurs when an end body is released during the rotation. The transfer of momentum to the released object will cause the rotating tether to lose energy, and thus lose velocity and altitude. Using electrodynamic tether thrusting or ion propulsion, the system can then re-boost itself with little or no expenditure of consumable reaction mass.

TA 2.3: Advanced (TRL < 3) Propulsion Technologies

Advanced Propulsion Technologies are those that use chemical or non-chemical physics to produce thrust, but are generally considered to be of lower technical maturity (TRL < 3) than those described in sections 2.1 and 2.2. Gravity assist is often used in conjunction with in-space propulsion to provide the required mission delta-V, but does not directly influence or impact in-space propulsion technology candidates discussed here. AeroGravity Assist is covered in TA 9 Entry, Descent, and Landing Systems.

Development of technology candidates within the area of advanced propulsion could result in breakthroughs that enable missions not previously possible with existing forms of propulsion technologies. The systems briefly described here have the potential to provide new ways to reach beyond LEO, deliver more mass to destinations, provide ultra-high delta-V capability, process very high power levels, and enable rapid transit times to destinations deep in the solar system and beyond. In some instances, development of technology candidates within this area will result in mission-enabling breakthroughs that will revolutionize space exploration. However, all of the concepts described in this section are very early in the technology development lifecycle, and require considerable work to mature the technology concepts for mission demonstration and consideration. Development of these technology candidates, even before there is a specified mission need, can improve the propulsion technology pipeline. Doing so will allow future mission planners to consider bolder missions to more distant destinations.

Sub-Goals

Section 2.3 includes technology candidate solutions that are very early in the technology development life cycle. As such, their near-term objectives should center on maturing the technology concept to the point of infusion into section 2.1 or 2.2. While they may be effective at greatly enhancing a current mission being considered by the Agency, they are not on the critical path for any currently planned mission. If these technology concepts are matured and developed, they might become available to future mission planners and enable missions not currently feasible using the solutions described in sections 2.1 and 2.2.

Table 15. Summary of Level 2.3 Sub-Goals, Objectives, Challenges, and Benefits

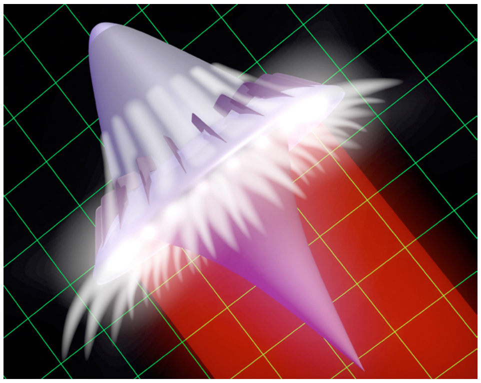
Level 1		
2.0 In-Space Propulsion Technologies	Goals:	Enhance current missions and open up new mission opportunities through improvements in performance, manufacturability, durability, and cost; and development of new propulsion capabilities.
Level 2		
2.3 Advanced (TRL < 3) Propulsion Technologies	Sub-Goals:	Provide propulsion capabilities to enable missions that are not feasible using current propulsion solutions.
Level 3		
2.3.1 Beamed Energy Propulsion	Objectives:	Provide propulsion energy beamed from ground or space-based stations
	Challenges:	Very large laser with adaptive real-time optics, advanced ceramic composites, and cooling and optics technology. Considerable ground infrastructure or in-space infrastructure to develop and beam the power.
	Benefits:	Provides a propulsion system capable of delivering low thrust with a high I_{sp}.

Table 15. Summary of Level 2.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
2.3.2 Electric Sail Propulsion	Objectives:	Generate sufficient force from interactions with the solar wind to propel a spacecraft.
	Challenges:	Deployment and control of long-life, extremely long bare wires.
	Benefits:	Allows for rapid transit times (estimated to be less than 15 years) to the outer solar system, the heliopause, and beyond (> 250 AU).
2.3.3 Fusion Propulsion	Objectives:	Develop and demonstrate fusion propulsion approaches. Achieve and maintain temperatures and densities required for fusion.
	Challenges:	Achieving high-energy gains (10 -100 times). Materials withstanding high temperature and radiation. Efficient conversion to directed jet power for thrust.
	Benefits:	Provide slow-mass, long-life, very high delta-V capabilities for future missions with power levels in the gigawatts. Hybrids can reduce the overall mass of the propulsion system by an order of magnitude relative to full fusion concepts.
2.3.4 High-Energy-Density Materials	Objectives:	Convert the large amounts of stored chemical energy into usable thrust.
	Challenges:	Manufacture and safe storage.
	Benefits:	Increases rocket engine I_{sp} by 1.5 to 4 times that of conventional oxygen/hydrogen chemical propulsion. Reduces required liftoff mass by 50 to 80 percent over oxygen/hydrogen propulsion systems.
2.3.5 Antimatter Propulsion	Objectives:	Provide a long-life, ultra-high delta-V primary propulsion system.
	Challenges:	Generation and storage of the antimatter. Bulk annihilation experiments require more experimental data because they are less understood and verified than single-particle annihilations.
	Benefits:	Provides a long-life, ultra-high delta-V primary propulsion system capable of processing very high power levels and enabling rapid transit missions to the outer solar system and interstellar precursor mission (e.g., 1,000 AU).
2.3.6 Advanced Fission	Objectives:	Increase thrust and I_{sp} over solid core NTP.
	Challenges:	Acceptable reactor fuel containment and high temperature and radiation resistance. Start-up and shutdown, engine cooling, and how best to perform qualification tests for open cycle. High-temperature materials, understanding mass transfer from molten fuel surface, stability of liquid core, heat transfer, and side effects of any liquid core rotations for liquid core. For nuclear pulse unit design, degree of collimation, pusher plate interaction, and system dynamic responses.
	Benefits:	Provides high thrust and I_{sp} two to three times that of solid core NTP, allowing faster trip times.
2.3.7 Breakthrough Propulsion	Objectives:	Provide propulsion capabilities to enable missions that are not feasible using current propulsion solutions.
	Challenges:	Work in this area routinely involves detailed scientific work, as the physics is still quite early in development. This area also requires modest, but sustained development as it is difficult to know which lines of investigation will yield promising propulsion breakthroughs in the absence of laboratory investigation.
	Benefits:	Provides long-life, ultra-high delta-V primary propulsion and rapid transit solutions capable of reaching ultra-distant destinations in the outer solar system, interstellar precursor missions, and possibly even initial robotic interstellar missions.

TA 2.3.1 Beamed Energy Propulsion

Beamed-energy propulsion uses laser or microwave energy from a ground- or space-based energy source and beams it to an orbital vehicle, which uses it to heat a propellant, with the advantage being a high exit velocity of exhaust products over traditional chemical propulsion. Earth-to-orbit laser propulsion technology has been investigated both analytically and experimentally as a first step to orbital transfer. In-space applications to be demonstrated are orbit transfer and Earth escape.



Beamed Energy Propulsion Concept Vehicle

Technical Capability Objectives and Challenges

The long-term objective for beamed energy propulsion is to achieve orbit transfer using a high I_{sp} propulsion system that receives power from ground- or space-based stations. The challenges include the need for a very large laser with adaptive real-time optics, advanced ceramic composites, cooling, and optics technology. An issue to be addressed with this category is the need for considerable ground infrastructure or in-space infrastructure to develop and beam the power.

Benefits of Technology

The significant advantage to this approach is having a propulsion system capable of delivering low thrust with a high I_{sp}. This performance capability is only possible because the system gets its power from an array of ground stations or an array of in-space power systems beaming power to the spacecraft.

Table 16. TA 2.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.1.1	Beamed Energy Propulsion	Beamed-energy propulsion uses laser or microwave energy from a ground- or space-based energy source and beams it to an orbital vehicle, which uses it to: 1) heat a propellant, or 2) reflect beamed energy to generate momentum.

TA 2.3.2 Electric Sail Propulsion

Electric sails operate through the exchange of momentum between an array of long, electrically-biased wires and solar wind protons, which flow radially away from the sun at speeds ranging from 300 to 700 kilometers per second (km/s). A high-voltage, positive bias on the wires, which are oriented normal to the solar wind flow, deflects the streaming protons and results in a reaction force on the wires that is also directed radially away from the sun. Over a period of months, this small force can accelerate the spacecraft to enormous speeds—on the order of 100 to 150 km/s (~ 20 to 30 AU/year).

Technical Capability Objectives and Challenges

This area of solar-proton interaction with charged wires will need to be investigated further to determine how great a force can be generated by the repulsion of the solar wind protons. In addition, any spacecraft that has an electric sail propulsion concept will likely be in a spin rotation as it traverses the solar system. As such, the charged bare-wires (< 30 km in length) must be deployed as the spacecraft is spinning. The development of long-life, extremely long bare wires may be a challenge.

Benefits of Technology

Electric sails allow for rapid transit times (estimated to be less than 15 years) to the outer solar system, the heliopause, and beyond (> 250 AU). The main principle that allows this quick trip time to be achieved is that the electric sail continually accelerates to distances of 30 AU from the sun, which greatly enhances the final velocity achieved versus current or planned future chemical propulsion or solar sail propulsion.

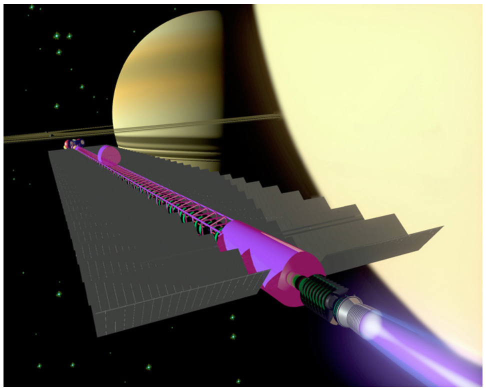
Table 17. TA 2.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.2.1	Electric Sail Propulsion	Provide thrust by reflecting charged particles from long, charged wires extended from a spacecraft in the solar wind, using no propellant to provide thrust.

TA 2.3.3 Fusion Propulsion

Fusion propulsion involves using fusion reactions to produce the energy required for the spacecraft primary propulsion. This can be accomplished either indirectly, with a fusion reactor producing electrical power that is in turn utilized in an electric thruster, or directly, by using the thermal/kinetic energy resulting from the fusion reactions to accelerate a propellant.

A variety of fusion propulsion concepts exist, which can be categorized as either inertial confinement fusion (ICF), magnetic confinement fusion (MCF), magneto-inertial fusion (MIF), or inertial electrostatic confinement (IEC). In the ICF fusion approach, high-intensity lasers strike the fusion target from multiple directions to rapidly compress the target to near-degenerate densities, and can achieve specific impulses of more than 100,000 seconds. In the MCF approach, plasma is contained in magnetic fields, and can achieve specific impulses in the 30,000 to 100,000 seconds range. In the MIF approach, plasma is confined magnetically while being impacted inertially with external materials from a z-pinch, dense plasma focus, or plasma gun. MIF fusion can achieve specific impulses in the 30,000 to 70,000 seconds range. The IEC concept creates an electrostatic potential between a center and outer shell, which confines and accelerates the plasma.



Fusion Propulsion Concept

Some of the full fusion approaches just discussed may be preceded by a fission-fusion hybrid approach. Fission-fusion hybrids offer a development path towards full fusion propulsion using existing, proven technologies. The most popular concept for a steady-state fission-fusion hybrid is applied to power generation and nuclear waste disposal, rather than propulsion applications. Here, the fusion plasma is brought to a condition where it produces neutrons (but not to a gain of unity) to bombard the fission shell and promote more complete burn up of the fission fuel. In the pulsed, antimatter catalyzed approach the initial energy release is driven by a matter-antimatter explosion, releasing enough energy to compress and drive fission reactions. The steady-state, antimatter catalyzed approach uses a confined fusion plasma that has injected antimatter and fissionable fuel. The antimatter catalyzes the fission of the fission fuel, boosting the energy of the fusion fuel. Performance for these hybrid systems can offer specific impulses between 5,000 and 100,000 seconds and thrust to weight ratios from 0.1 to well above unity.

Technical Capability Objectives and Challenges

The objective for this technology is to demonstrate a fusion propulsion approach in a laboratory environment and measure performance parameters. Challenges include achieving high energy gains (10 to 100 times), materials withstanding high temperature and radiation, and efficient conversion to directed jet power for thrust. I_{sp} can range from 10,000 to 100,000 seconds. Fusion reactions require reaching a certain temperature level so that a fraction of the fusion fuel reaches the kinetic energy to crash into another fusing molecule with enough force to overcome their electrostatic repulsion from their respective electron clouds and their nuclei. At that point, the nuclei can fuse, releasing an amount of energy an order of magnitude greater than fission. Each fusion concept approaches this challenge in a different manner. Some achieve very high temperatures and densities for a fraction of a second, while others hold the plasma at a lower temperature for a longer period of time.

Benefits of Technology

Fusion propulsion has the potential to provide low-mass, long-life, very high delta-V capabilities for future missions with power levels in the gigawatts. Fusion propulsion has the potential to enable human exploration missions of the outer solar system and robotic exploration of near-interstellar space. Fission-fusion hybrids also show potential to reduce the overall mass of the propulsion system by an order of magnitude relative to full fusion concepts.

Table 18. TA 2.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.3.1	Fusion Propulsion	Fusion propulsion utilizes fusion energy to generate thrust or electric power for other propulsion concepts. Configurations can operate in steady state or repetitive pulse modes.

TA 2.3.4 High-Energy-Density Materials

High-energy-density materials are characterized by atoms trapped in solid cryogens (e.g., neon). Atomic hydrogen, boron, and carbon fuels are very high-energy-density, free-radical propellants. Atomic hydrogen may deliver an I_{sp} of 600 to 1,500 seconds. Atom storage density has improved greatly over the last several decades. Lab studies have demonstrated 0.2 and 2 weight percent atomic hydrogen in a solid hydrogen matrix. If the atom storage were to reach 10 to 15 percent, that amount would produce an I_{sp} of 600 to 750 seconds.

Technical Capability Objectives and Challenges

High-energy-density materials have large amounts of stored chemical energy, with complex chemical structures or atoms stored in frozen cryogenic molecular matrices. The technology can deliver revolutionary increases in rocket engine I_{sp} and many-fold increases in vehicle payload mass.

Benefits of Technology

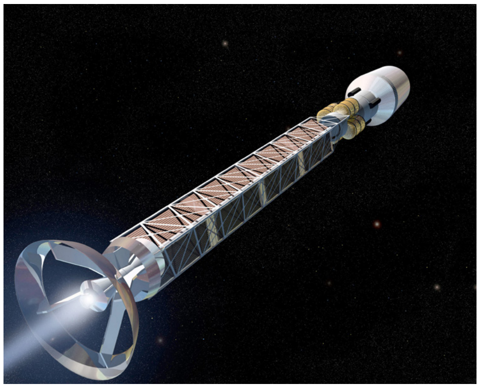
Rocket engine I_{sp} can be increased to 1.5 to 4 times that of conventional oxygen/hydrogen chemical propulsion. Studies have shown a reduction in the required liftoff mass of 50 to 80 percent over oxygen/hydrogen propulsion systems.

Table 19. TA 2.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.4.1	Metallic Hydrogen	High energy density, extremely high-pressure (> 1,000,000 pounds per square inch (psi)) state of hydrogen that has large amounts of stored chemical energy (with complex chemical structures or atoms stored in frozen solid cryogenic molecular matrices).
2.3.4.2	Atomic Boron/Carbon/Hydrogen	Atomic boron, carbon, and hydrogen have large amounts of stored chemical energy (with complex chemical structures or atoms stored in frozen cryogenic molecular matrices or solid cryogens).
2.3.4.3	High Nitrogen Compounds (N_4+, N_5+)	High-nitrogen compounds have large amounts of stored chemical energy (with complex chemical structures or atoms in metastable room-temperature chemical solids). These are the most powerful chemical explosives ever created.

TA 2.3.5 Antimatter Propulsion

Antimatter propulsion uses the high energy from antimatter annihilation to increase propulsion performance. The amount of performance gain depends on the amount of antimatter used. Particle accelerators produce nanogram quantities of antiprotons worldwide each year for science. Small quantities have been stored for short durations by different concepts. The formation of anti-hydrogen has been demonstrated. No propulsion proof-of-concept has been made. The near-term primary challenge is to mature a propulsion concept that only needs small quantities of antimatter (micrograms or less).



Antimatter Propulsion Concept Vehicle

Technical Capability Objectives and Challenges

The preliminary objective for this category of advanced propulsion is to design and conduct a proof-of-principle experiment to demonstrate a propulsive application (i.e., antimatter on target to produce energy for propulsion). The target geometry would depend on concept approach and could range from a catalyzed pellet to a formed, sail-type material. The experiment would provide data on thrust magnitude, impulse, and overall efficiency. There are two concerns to address. First, bulk annihilation experiments require more experimental data because they are less understood and verified than single-particle annihilations. The generation and storage of the antimatter is a second system concern to address.

Benefits of Technology

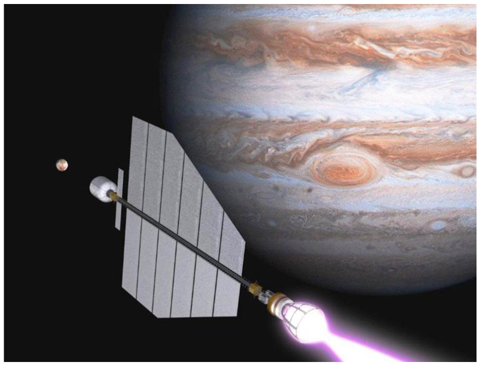
An antimatter-based propulsion system could provide a long-life, ultra-high delta-V primary propulsion system capable of processing very high power levels and enabling rapid transit missions to the outer solar system and interstellar precursor mission (e.g., 1,000 AU).

Table 20. TA 2.3.5 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.5.1	Antimatter Propulsion	Antimatter propulsion is based on conversion of a large percentage (up to ~75%) of fuel mass into propulsive energy by annihilation of atomic particles with their antiparticles.

TA 2.3.6 Advanced Fission

Advanced fission propulsion has three different concepts: gas and liquid core nuclear thermal, fission-fragment, and external-pulsed plasma propulsion. These utilize the fission-produced energy in different ways for greater I_{sp} than can be achieved with solid core NTP.



Fission Fragment Propulsion Concept Vehicle

Gas and liquid core nuclear thermal concepts have a gaseous or liquid reactor and are similar to solid core NTP, which was discussed in section 2.2.3. Both gas and liquid core nuclear thermal propulsion concepts heat a propellant, which undergoes thermal expansion and is released through a traditional nozzle. Two gas core concepts have been investigated. The open cycle concept relies on fluid dynamics or electromagnetics to contain the reactor core and minimize fuel loss. The closed cycle concept relies on a transparent wall to contain the nuclear fuel and uses a seeded propellant. Liquid core concepts rotate the molten reactor fuel.

Fission fragment propulsion uses naturally-occurring fission fragments (FFs) to directly or indirectly produce thrust. Direct thrust utilizing high exit velocity (~3 to 5 percent the speed of light) fission fragments could provide I_{sp} at ~500,000 seconds and thrust of ~10 lbf. Indirect thrust uses the fission fragments in a magnetic beam to heat a propellant and provide higher thrust of ~1,000 lbf, with a reduced I_{sp} at ~30,000 seconds.

External-pulse plasma propulsion operates with small nuclear pulse units ejected out the aft end of the spacecraft, which are then detonated to produce a force on the aft end pusher plate for high thrust and high I_{sp} for large spacecraft. Another pulsed system is the pulsed fission-fusion concept, which strives for much smaller and more rapid pulses, triggered by an external z-pinch. Steady state concepts exist, including the toroidal hybrid reactor and the antiproton gas dynamic mirror.

Technical Capability Objectives and Challenges

Gas and liquid core NTP need to advance from analytical results and proof of concept to component or subscale breadboard validations. Open-cycle challenges include fuel containment during steady state, start-up and shut-down, engine cooling, and how best to perform qualification tests. The closed-cycle challenge is developing a transparent wall capable of withstanding high temperatures, radiation, and erosion. Liquid core challenges include high-temperature materials, understanding mass transfer from molten fuel surface, stability of liquid core, heat transfer, and side effects of any liquid core rotations.

Fission fragment propulsion has been evaluated through analytical studies, and advancing fission fragment propulsion development requires proof of concept validation of a number of the system aspects. Experimental demonstrations of nuclear fuel control, self-cooling, efficiency of FF escape, and efficiency of mixing hydrogen with a FF beam are needed to benchmark the analytical models.

External-pulsed plasma propulsion has the potential for high thrust of approximately 500,000 lbf and high I_{sp} of greater than 5,000 seconds. More analytical system studies and a proof of concept are needed to validate these. Development challenges include the nuclear pulse unit design, degree of collimation, detonation position and fissile burn-up fraction, pusher plate plasma interaction, shock absorber efficiency, timing, and dynamic responses.

Benefits of Technology

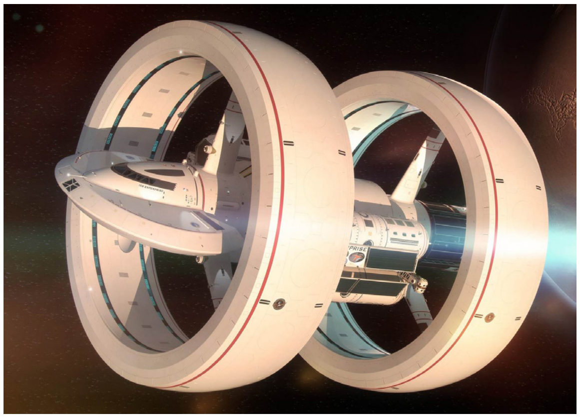
Gas and liquid core NTP provide high thrust and I_{sp} two to three times that of solid core NTP, allowing faster trip times. The FF propulsion has the ability to vary the mass flow of an added neutral propellant so that the engine thrust and I_{sp} can be optimized for faster missions beyond Mars without altering the engine. External-pulse plasma propulsion provides a simple and efficient direct use of nuclear energy to generate high thrust and I_{sp} for large spacecraft with destinations to Mars and beyond.

Table 21. TA 2.3.6 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.6.1	Gas and Liquid Core Nuclear Thermal Propulsion	Gas and liquid core NTP is similar to solid core NTP except the fission reactor core is either gaseous or liquid. Two gas core concepts have been investigated. The open cycle concept relies on fluid dynamics or electromagnetics to contain the reactor core and minimize fuel loss. The closed cycle concept relies on a transparent wall to contain the nuclear fuel and uses a seeded propellant. Liquid core concepts rotate the molten reactor fuel.
2.3.6.2	Fission Fragment Propulsion	The high kinetic energy (~3-5% the speed of light) of ionized fission fragments is guided with a magnetic nozzle and directly used to produce thrust or used indirectly to heat a propellant for higher thrust.
2.3.6.3	External Pulsed Plasma Propulsion	Small directional nuclear pulse units are ejected at the aft end of the spacecraft and detonated. Thrust is produced by momentum exchange with a large pusher plate and shock absorbers on the aft end of the spacecraft.

TA 2.3.7 Breakthrough Propulsion

Breakthrough propulsion is an area of technology development that seeks to explore and develop a deeper understanding of the nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomena with the overall objective of developing advanced propulsion applications and systems that will revolutionize space exploration.



Breakthrough Propulsion Concept Vehicle

Technical Capability Objectives and Challenges

Breakthrough propulsion is applied scientific research specifically looking for propulsion breakthroughs from physics. Immediate objectives for concepts in this category should first seek to demonstrate existence of the proposed physical phenomenon or proof of principle of a new application seeking to gather relevant performance data. This includes creating new concepts and conducting independent verification and validation of experimental data.

Benefits of Technology

Propulsion concepts in this category have the potential to enable long-life, ultra-high delta-V primary propulsion, and rapid transit solutions capable of reaching ultra-distant destinations in the outer solar system, interstellar precursor missions, and possibly even initial robotic interstellar missions.

Table 22. TA 2.3.7 Technology Candidates – not in priority order

TA	Technology Name	Description
2.3.7.1	Breakthrough Propulsion	Breakthrough propulsion is applied scientific research specifically looking for propulsion breakthroughs from emerging physics.

TA 2.4: Supporting Technologies

Supporting Technologies are those technologies that support an in-space propulsion system or subsystem but are not directly propulsive. The supporting technology candidates include pervasive technologies (integrated system health management, materials and structures, heat rejection, and power) and cryogenic fluid management (CFM) for propellants. In addition, the need for analytical and computational modeling across the in-space technology category is discussed. For the pervasive technologies, technology gaps for propulsion application are identified in the preceding sections and are embedded in the text of the individual propulsion technology supported. In each case, the TA that addresses these needs is identified below. For CFM and transfer, thermal control components are addressed in detail in TA 14 Thermal Management Systems, whereas microgravity fluid dynamics and the integration of the thermal control and fluid management technologies are covered in this TA. There is also a need for future propulsion systems to be more serviceable and maintainable as system life and reuse increase, and those requirements have been treated as embedded in the individual technology candidates, rather than a separate supporting technology candidate.

Advancing the analytical and computational propulsion modeling capability is critical to advancing and eventually implementing almost all in-space propulsion technologies. While advancing computational capabilities and developing new physics algorithms are discussed in TA 11 Modeling, Simulation, Information Technology, and Processing, developing capabilities into tools that can be used for technology and system development must also be pursued. These are tools that are more predictive (improved accuracy) in nature that the SOA physics-based and empirically-based heritage design tools. These tools are needed to describe the time varying fluid dynamic, thermal environments, and complex fluid/thermal/structural interactions necessary to design robust, efficient, and low-cost chemical, non-chemical, and advanced propulsion systems. Developing these tools is integral to the development of the specific technologies to which they are applied. In some cases, the technology descriptions in earlier sections explicitly identify needed tools development; where tool development or advancement is not explicitly identified, it is implied as a parallel activity to support the technology development.

Sub-Goals

Improve the capability of propulsion systems to increase the efficiency and flexibility of exploration and science missions.

Table 23. Summary of Level 2.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
2.0 In-Space Propulsion Technologies	Goals:	Enhance current missions and open up new mission opportunities through improvements in performance, manufacturability, durability, and cost; and development of new propulsion capabilities.
Level 2		
2.4 Supporting Technologies	Sub-Goals:	Improve the capability of propulsion systems to increase the efficiency and flexibility of exploration and science missions.
Level 3		
2.4.1 Engine Health Monitoring and Safety	Engine Health Monitoring and Safety technologies are addressed in the roadmaps for TA 4 Robotics and Autonomous Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology, and Processing, and TA 12 Materials, Structures, Mechanical Systems, and Manufacturing.	

Table 23. Summary of Level 2.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
2.4.2 Propellant Storage and Transfer	Objectives:	Reduce and eventually eliminate boil-off. Develop efficient tank-to-tank transfer of cryogenic propellant.
	Challenges:	Testing and validation at the scale required for crewed exploration. Testing in the microgravity environment.
	Benefits:	Increases efficiency and flexibility of missions for exploration beyond LEO. Reduces overall mission mass, multiple mission launches can be spaced further apart, and low-cost launch options can be developed to resupply propellant to in-space stages.
2.4.3 Materials and Manufacturing Technologies	Materials and Manufacturing technologies are addressed in the roadmaps for TA 10 Nanotechnology and TA 12 Materials, Structures, Mechanical Systems, and Manufacturing.	
2.4.4 Heat Rejection	Heat Rejection technologies are addressed in the roadmap for TA 14 Thermal Management Systems.	
2.4.5 Power	Power technologies are addressed in the roadmap for TA 3 Space Power and Energy Storage.	

TA 2.4.1 Engine Health Monitoring and Safety

Integrated System Health Management, as applied to propulsion, relies on automating interpretation, reasoning, and decision making based on data collected during the processing and operation of the propulsion system to enable anomaly detection, diagnostics, prediction of future anomalies (prognostics), and intuitive and rapid integrated awareness about configuration and condition of every element in a system. Technology roadmaps for TA 4 Robotics and Autonomous Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology, and Processing, and TA 12 Materials, Structures, Mechanical Systems, and Manufacturing provide descriptions of the SOA, as well as specific technology candidate snapshots.

TA 2.4.2 Propellant Storage and Transfer

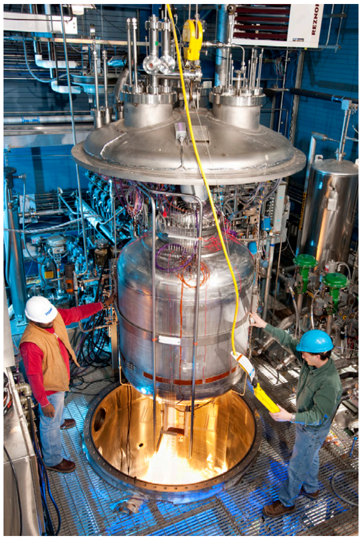
CFM broadly describes the suite of technologies that can be used to enable the efficient in-space use of cryogens despite their propensity to absorb environmental heat, their complex thermodynamic and fluid dynamic behavior in low gravity, and the uncertainty of the position of the liquid-vapor interface when propellants are not settled.

LO_2 Zero Boil-off Demonstration Test Article

Technical Capability Objectives and Challenges

Current cryogenic propellant upper stages are limited to a few hours of loiter in space before using the propellant, in large part due to high propellant losses due to boil-off. This time constraint limits the flexibility and capability of crewed exploration missions. Technology advances in insulation and shading, low thermal conductivity structures, thermodynamic venting, and active thermal control (cryocooler refrigeration) can greatly extend storage time and mission life for in-space propulsion stages. The early objectives are to reduce boil-off by an order of magnitude, with the longer-range objective of eliminating boil-off losses altogether. Current cryogenic propellant-gauging methods require the stage to be accelerated significantly to firmly settle the propellant such that a propellant level measurement can be accurate. For long-duration missions, alternative methods of gauging are required to eliminate the need for settling the propellant. Finally, an additional range of mission architectures (relying on propellant tankers or in-space depots) can be enabled, if propulsion stages can be filled or refilled in orbit. Technologies that enable efficient tank-to-tank transfer of cryogenic propellant in space need to be developed (note that NASA has also recently advanced the technologies needed to refuel non-cryogenic in space propellant systems robotically).

The two main development challenges for all of these technologies are that they need to be tested and validated at the scale required for crewed exploration, and tested in the microgravity environment.



Liquid Acquisition Device Test Article for LH_2 Outflow and Transfer Chill Down

Benefits of Technology

Advanced cryogenic propellant storage and transfer technologies enable more efficient and flexible missions for exploration beyond LEO. Overall launch mass can be reduced, multiple mission launches can be spaced further apart, and low-cost launch options can be developed to resupply propellant to in-space stages.

In addition to the capability benefits that are specific to the propellant system, it is possible that these propellant storage and transfer technologies can be leveraged to develop a system that enables power generation, pressurization, and auxiliary propulsion functions to utilize the main propellant tank fluids. If this can be done efficiently, elimination of a separate auxiliary propellant system and downsizing of energy generation and storage systems may reduce the vehicle mass.

Table 24. TA 2.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
2.4.2.1	Passive Thermal Control for Cryogenic Propellants	Advanced insulation, solar shields, low conductivity structure, thermodynamic venting, and vapor cooling to reduce the heat load entering the tank that causes boil-off.
2.4.2.2	Active Thermal Control	Integrates cryocooling with the propellant tank system to reduce or eliminate the heat load entering the tank that causes boil-off.
2.4.2.3	In-Space Tank-to-Tank Propellant Transfer	High-efficiency line and tank chill-down, followed by no-vent transfer and fill of a receiving propellant tank.
2.4.2.4	In-Space Propellant Gauging	Accurate measurement of cryogenic liquid propellant quantity in space without propulsive settling maneuvers.

TA 2.4.3 Materials and Manufacturing Technologies

Structures, materials, and manufacturing play a critical role in all in-space propulsion systems for both human and robotic missions. Material, structural, or manufacturing advances are required to enable propulsion technology advances. In other cases, the structural and material advances are enhancing, or can result in a significant propulsion system improvement of their own. In general, propulsion systems are looking for improvements in high temperature capability, weight, cost, and time for manufacturing. Technology roadmaps for TA 10 Nanotechnology and TA 12 Materials, Structures, Mechanical Systems, and Manufacturing provide descriptions of the SOA, as well as specific technology development recommendations.

TA 2.4.4 Heat Rejection

Heat rejection is a key supporting capability for several in-space propulsion systems. Some examples include rejection of the waste heat generated due to inefficiencies in electric and thermal propulsion devices, and rejection of the heat removed from a cryogenic propellant storage system by a cryocooler. The roadmap for TA 14 Thermal Management Systems provides a description of the SOA, as well specific technology development recommendations. In general, the key heat rejection system metrics for in-space propulsion are cost, weight, operating temperature, and environmental durability (e.g., radiation, MMOD).

TA 2.4.5 Power

Power systems play an integral role in all in-space propulsion systems for both human and robotic missions. The roadmap for TA 3 Space Power and Energy Storage provides a description of the SOA, as well as specific technology development recommendations. In some cases, power is only required for basic functions of instrumentation and controls, and technology advances are not required. In other cases the propulsion energy of the technology is derived from electrical power generation, management, and distribution, and power system technology advances are critical for the advancement of the propulsion system (e.g., high-power solar or nuclear electric propulsion, beamed energy). Central to the nuclear electric challenge is the need for high thermal power conversion efficiency, coupled with the heat rejection technology mentioned above. In general, the key power system metrics for in-space propulsion are cost, reliability, specific power, operating ranges (power and environmental), and maximum power generation.

Appendix

Acronyms

CFM	Cryogenic Fluid Management
DRA	Design Reference Architecture
DRM	Design Reference Mission
EVA	ExtraVehicular Activity
FF	Fission Fragments
HPGP	High Perfomance Green Propellant
HTPB	Hydroxyl-Terminated PolyButadiene
ICF	Inertial Confinement Fusion
IEC	Inertial Electrostatic Confinement
IMLEO	Initial Mass in Low-Earth Orbit
L1	Lagrange Point 1
LEO	Low-Earth Orbit
MCF	Magnetic Confinement Fusion
MEMS	MicroElectroMechanical Systems
MIF	Magneto-Inertial Fusion
MMOD	MicroMeteoroid and Orbital Debris
MPD	MagnetoPlasmaDynamic
MPS	Main Propulsion System
NEA	Near-Earth Asteroids
NEXIS	Nuclear Electric Xenon Ion System
NEXT	NASA Evolutionary Xenon Thruster
NSTAR	NASA Solar Technology Application Readiness
NTP	Nuclear Thermal Propulsion
OCT	Office of the Chief Technologist
PPU	Power Processing Unit
RCS	Reaction Control Systems
RF	Radio Frequency
RP	Rocket Propellant
SCAPE	Self Contained Atmospheric Protective Ensemble
SEP	Solar Electric Propulsion
SLS	Space Launch System
SMD	Science Mission Directorate
SOA	State Of the Art
STIP	Strategic Technology Investment Plan
STP	Solar Thermal Propulsion
SWaP	Size, Weight, and Power
TA	Technology Area
TABS	Technology Area Breakdown Structure
TRL	Technology Readiness Level
U.S.	United States
VASIMR	Variable Specific Impulse Magnetoplasma Rocket

Abbreviations and Units

Abbreviation	Definition
%	Percent
A	Ampere
ADN	Ammonium Dinitramide
AN	Ammonium Nitrate
AP	Ammonium Perchlorate
AU	Astronomical Units
C	Celsius
CH_4	Methane
ClF_3	Chlorine trifluoride
ClF_5	Chlorine pentafluoride
cm^3	Cubic centimeters
° F	Fahrenheit
F	Thrust
F_2	Fluorine
ft	foot
g	Grams
g/m^2	Grams per square meter
GN	Gaseous nitrogen
H_2	Hydrogen
HCL	Hydrogen Chloride
He	Helium
Hrs	Hours
I_{sp}	Specific Impulse
Li	Lithium
K	Kelvin
k	Kilo
kg	Kilograms
khr	1,000 Hours
kJ	Kilo-Joule
klbf	Kilo pounds-force
km	Kilometers
km/s	Kilometers per second
kN	KiloNewtons
kV	KiloVolt
kW	KiloWatt
kWe	KiloWatt electrical
lb*s	Pounds-seconds
lbf	Pounds-force

Abbreviation	Definition
LCH_4	Liquid Methane
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen
LO_2/LCH_4	Liquid oxygen/Methane
LO_2/N_2H_4	Liquid oxygen/Hydrazine
LOX	Liquid Oxygen
m	Meters
m^2	Square Meters
m/cda	Ballistic coefficient
MF	mass fraction
MMH	Monomethyl hydrazine
mN	MilliNewton
mN/kW	MilliNewton per kiloWatt
m/s	Meters per second
msec	Milliseconds
MW	MegaWatt
N	Newtons
N s	Newton-second
N_2	Nitrogen
N/kW	Newton per kiloWatt
N_2H_4	Hydrazine
N_2O/HTPB	Nitrous Oxide/Hydroxyl-Terminated Polybutadiene
H_2O_2/HTPB	Hydrogen Peroxide/ Hydroxyl-Terminated Polybutadiene
NTO	Nitrogen Tetroxide
NTO/MMH	Nitrogen Tetroxide / Monomethyl Hydrazine
O_2	Oxygen
O_2/H_2	Oxygen/Hydrogen
OF_2	Oxygen Difluoride
PPU	Power Processing Unit
psi	Pounds Per Square Inch
Q	Fusion energy gain
s	Seconds
$s*kg/m^3$	Second kilograms per meter cubed
µNs	Micro Newton-seconds
V	Volts
W	Watts
W/m^2	Watt per meter squared
W/mN	Watts per milliNewton
Xe135	Xenon 135

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Technology Candidate Snapshots

2.1 Chemical Propulsion
2.1.1 Liquid Storable

2.1.1.1 Monopropellants

TECHNOLOGY

Technology Description: Monopropellant thrusters use a single Earth- and space-storable propellant decomposed to generate high-temperature gas for thrust.

Technology Challenge: More development of higher thrust classes needs to occur to be comparable to the current regime of hydrazine thrusters. Scaling may need alternate ignition developments as preheat power will grow. Development of catalysts with extended life and operational regimes is also needed. The developed propellants generally require preheat and do not cold start. Some candidates may need a reduction of freezing point without compromising performance.

Technology State of the Art: European: flight test demonstration of 1 N (1st generation propellant).

U.S.: pending flight test demonstration of 1 N and 22 N 1st generation propellant, ground (sea level and altitude) demonstrations of up to 445 N (the High Perfomance Green Propellant (HPGP)).

Parameter, Value:

European 1st generation: 1 N flown, 0.5 N to 22 N ground demo, density specific impulse (I_{sp}) = 278 to 309 s*kg/m³, preheat = 350° C;

U.S. 1st generation: 0.5 N to 22 N ground demo, density I_{sp} = 350 to 375 s*kg/m³, preheat = 370° C;

Nitrous oxide fuel blend: 0.44 N to 445 N ground demo, density I_{sp} = 291.4 s*kg/m³

TRL 3

Technology Performance Goal: High-achieved density, I_{sp}, long-life catalysts, and increased thrust level.

Parameter, Value:

Density-I_{sp} increase of 50% for 1st generation and 70% for 2nd generation;

Thruster operating life: > SOA for a given application;

Thrust: > 445 N

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High density-I_{sp} with reduced toxicity and low preheat requirement for reaction control and main propulsion.

Capability Description: Reaction control thrusters provide small accelerations to maintian or adjust a spacecraft's attitude or provide spacecraft orbit manueviering. For primary propulsion engines, provide spacecraft orbit manueviering, orbit insertion, or ascent propulsion with high I_{sp}.

Capability State of the Art: Reaction control/main propulsion systems utilizing hydrazine decomposition.

Parameter, Value: Hydrazine:

< 1 N thrusters: I_{sp} = 200 to 230 s (SmallSat);

1 N to 22 N thrusters: I_{sp} = 200 to 235 s (SmallSat attitude control system (ACS)/reaction control system (RCS)/Primary);

> 22 N thrusters: I_{sp} = 200 to 245 s ("Traditional"/Manned Scale ACS/RCS/Primary)

Capability Performance Goal: Achieve better-than-state of the art (SOA) hydrazine performance (e.g., improved I_{sp} or density-I_{sp}, greater storage temperature range, longer catalyst life, etc.) with lower operational handling and transport requirements (e.g., no Self-Contained Atmosphere Protective Ensemble (SCAPE) suits required, with less restrictive transportation methods); goals are 50% improvement in density-I_{sp}.

Parameter, Value:

Propellant with improved (less costly, safer) ground handling versus the SOA.

Propulsion system with equivalent or reduced overall system mass versus the SOA.

Density-I_{sp}: increase of 50% for 1st generation and 70% for 2nd generation.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Discovery 14	Enhancing	--	2023	2020	3-5 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	3-5 years

2.1 Chemical Propulsion
2.1.1 Liquid Storable

2.1.1.2 Bipropellants

TECHNOLOGY

Technology Description: Bipropellant thrusters use Earth- and space-storable propellant to generate a chemical reaction, typically hypergolic, to produce high-temperature gas that is expanded to generate thrust.

Technology Challenge: Challenges include reliable ignition in vacuum and comparable ignition delay to nitrogen tetroxide (NTO) monomethyl hydrazine (MMH), increased thrust with improved packaging for landers and orbit insertion, and throttle capability for planetary landers. Pumped systems are desirable for planetary spacecraft versus pressure fed systems. Also needed are mixture ratio control and propellant gauging to reduce residuals and improve performance and reduced-toxicity propellants for safety and reduction of handling costs.

Technology State of the Art: Some low-Technology Readiness Level (TRL) studies of green or reduced toxicity hypergolic bipropellants have been carried out.

Parameter, Value: | **TRL**

Reduced toxicity, hypergolic behavior, and theoretically improved performance. | 3

Technology Performance Goal: High-performance green and hypergolic propellant alternatives with minimum igntion delay.

Parameter, Value: | **TRL**

Specific impulse (I_{sp}): ≥ 20% over state of the art (SOA);

Ignition delay: ≤ NTO/MMH | 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High I_{sp} with reduced toxicity and short ignition delay for reaction control and main propulsion.

Capability Description: Provide spacecraft reaction control and attitude control, orbit manueviering, orbit insertion, or ascent/descent propulsion. For primary propulsion engines, provide spacecraft orbit manueviering, orbit insertion, or ascent propulsion with high I_{sp}.

Capability State of the Art: Orbitial manuevering and reaction control space engines using NTO/MMH with ablative combustion chambers.

Parameter, Value:

Nitrogen Tetroxide/Hydrazine: I_{sp} = 326 s for fixed thrust (450 N) planetary main engine; theoretical maximum I_{sp} = 341 s

Capability Performance Goal: Achieve better-than-SOA hypergolic bipropellant performance (e.g. improved I_{sp}, greater storage temperature range, etc.) with lower operational handling and transport requirements (e.g. no Self Contained Atmospheric Protective Ensemble (SCAPE) suits required, with less restrictive transportation methods).

Parameter, Value:

Propellant with improved (less costly, safer) ground handling compared to the SOA.

Propulsion system with equivalent or reduced system mass compared to the SOA.

I_{sp} ≥ 20% over SOA.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5-6 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5-6 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5-6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5-7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5-7 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5-7 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	5-6 years

2.1 Chemical Propulsion
2.1.1 Liquid Storable

2.1.1.3 High Energy Propellants

TECHNOLOGY

Technology Description: Higher energy propellant combinations can increase rocket engine performance and increase vehicle payload mass. An example is liquid oxygen/hydrazine (LO_2/N_2H_4), with 340 to 350 seconds of I_{sp}.

Technology Challenge: Challenges include valve leakage, spark ignition, boil-off management, and thermal environment. All of the associated feed system technologies need to be addressed.

Technology State of the Art: LO_2/N_2H_4 demonstrated in small-scale lab thruster.

Parameter, Value:

Parameter, Value	TRL
Specific Impulse (I_{sp}): ~ 340 seconds	5

Technology Performance Goal: Rocket engine I_{sp} is 10 to 50 seconds higher than that of conventional chemical propulsion.

Parameter, Value:

Parameter, Value	TRL
LO_2/N_2H_4 with 340 to 350 seconds of I_{sp}	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Increased space vehicle payload mass capability.

Capability Description: Significant payload increases can be enabled by increasing rocket engine I_{sp}, and high-energy propellants can increase I_{sp} by 10 to 50 seconds over nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) (with an I_{sp} value of 310 to 320 seconds, for thrust (F) = 100 lbf). Bipropellant thrusters use the chemical reactions to generate high-temperature gas that is expanded to generate thrust. One of the two may be cryogenic fluid and may also require spark ignition systems. LO_2/N_2H_4 is an option that has comparable performance to LO_2/LCH_4. Higher thrust levels are needed.

Capability State of the Art: NTO/MMH chemical rocket engines.

Parameter, Value:

I_{sp}: 310 seconds

Capability Performance Goal: Demonstrate spark ignition systems and long-term oxygen (O_2) storage in space environment. LO_2/N_2H_4 is an option that has comparable performance to liquid oxygen/methane (LO_2/LCH_4). Higher thrust levels are needed.

Parameter, Value:

Thrust: > 100 lbf (likely 1,000 to 5,000 lbf);

I_{sp} increase: 10 to 50 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	9 years
New Frontiers: Push	Enhancing	--	--	--	10 years
Planetary Flagship: Push	Enhancing	--	--	--	10 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.1 Chemical Propulsion
2.1.1 Liquid Storable

2.1.1.4 High Energy Oxidizers

TECHNOLOGY

Technology Description: Fluorinated compounds can increase rocket I_{sp} by 10 to 70 seconds. An example is fluorine/hydrazine (F_2/N_2H_4) with 360 to 370 seconds of I_{sp}.

Technology Challenge: There are safety issues associtated wih the high reactivity for fluorine (F_2).

Technology State of the Art: Fluorine/hydrazine demonstrated in lab.

Parameter, Value: Specific impulse (I_{sp}): ~370 seconds

TRL: 6

Technology Performance Goal: Rocket engine I_{sp} is 50 to 70 seconds higher than that of conventional chemical propulsion.

Parameter, Value: 350 to 400 seconds

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Increased space vehicle payload mass capability.

Capability Description: Significant payload increases can be enabled by increasing rocket engine I_{sp} and high-energy propellants can increase I_{sp} by 10 to 70 seconds over nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) (with I_{sp} value of 310 to 320 seconds, for thrust (F) = 100 lbf). These high-density, high-energy oxidiers offer high rocket I_{sp} with hydrazine(s) for deep-space missions, as well as improved storablility over pure oxygen.

Capability State of the Art: NTO/MMH chemical rocket engines.

Parameter, Value: I_{sp}: 310 seconds

Capability Performance Goal: High-energy oxidizers such as fluorinated compounds include chlorine trifluoride (ClF_3), chlorine pentafluoride (ClF_5), and oxygen digluoride (OF_2). These oxidizers have a long history of testing, with most recent testing in the 1980s. Stages for interceptors were created for flight testing using ClF_5/hydrazine.

Parameter, Value: Thrust > 100 pounds force (lbf) (likely 1,000 to 5,000 lbf); I_{sp} increase 10 to 70 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	7 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.1 Chemical Propulsion
2.1.2 Liquid Cryogenic

2.1.2.1 Liquid Oxygen (LO_2), Methane (CH_4) Pressure-Fed Main Engine

TECHNOLOGY

Technology Description: Pressure-fed rocket engines for primary propulsion that use liquid methane as the fuel.

Technology Challenge: Methane as a propellant has not flown in an operational system. The system must have sufficient cryogenic fluid management to deliver the proper quality of propellant and demonstrate reliable ignition. The system must also demonstrate consistent peformance and reliability similar to existing state of the art (SOA), and operate as an integrated system with a reaction control system.

Technology State of the Art: Altitude testing of pressure-fed 5,500 lbf technology demonstration main engine with ablative cooling.

Parameter, Value:

Pressure-fed liquid oxygen (LO_2), methane (CH_4):

Specific impulse (I_{sp}): 355 seconds;

Thrust level: 5,500 lbf

TRL

4

Technology Performance Goal: Long-life, high-temperature combustion chambers. Reliable ignition systems. Efficent, high-performance injectors.

Parameter, Value:

Pressure-fed LO_2, CH_4:

I_{sp}: 355 seconds;

Thrust level: 7,500 lbf;

Operational life: 200+ seconds;

Number of restarts: 3+;

Throttling: 3:1

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High I_{sp} in-space planetary ascent and descent propulsion.

Capability Description: Provide spacecraft orbit maneuvering, orbit insertion, or ascent propulsion with high I_{sp}.

Capability State of the Art: Orbitial manuevering space engines using nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) with ablative combustion chambers.

Parameter, Value:

I_{sp}: 315.1 seconds;

Thrust level: 6,000 lbf;

Opertional life: 100 missions

Capability Performance Goal: Provide thrust for Earth orbit missions: orbital insertion, de-orbit, and abort. For Mars or lunar missions, the engine would be used for surface ascent or descent.

Parameter, Value:

Pressure-fed LO_2, CH_4:

I_{sp}: 355 seconds;

Thrust level: up to 40,000-lbf; Operational life: 1,000 seconds to 10 hours; Number of restarts: 3+;

Throttling: 5:1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years

2.1 Chemical Propulsion
2.1.2 Liquid Cryogenic

2.1.2.2 Liquid Oxygen (LO_2), Methane (CH_4) Pump-Fed Main Engine

TECHNOLOGY

Technology Description: Pump-fed rocket engines for primary propulsion that use liquid methane as the fuel.

Technology Challenge: Methane as a propellant has not flown in an operational system. The system must have sufficient cryogenic fluid management to deliver the proper quality of propellant and demonstrate reliable ignition. The system must also demonstrate consistent peformance and reliability similar to existing state of the art (SOA). Another challenge is the development of pump-fed engines that are stable and meet both the specific impulse (I_{sp}) and deep throttling performance requirements.

Technology State of the Art: NASA altitude testing of pressure-fed (not pump-fed) 5,500 lbf technology demonstration main engine with ablative cooling. Foreign government testing of 100 kN gas generator and regeneratively cooled thrust chamber assembly.

Parameter, Value:

Pressure-fed (not pump-fed) liquid oxygen (LO_2), methane (CH_4):

I_{sp}: 355 seconds;

Thrust level; 5,500 lbf

TRL

3

Technology Performance Goal: Long-life, high-temperature, regenerative-cooled combustion chambers. Reliable ignition systems. Efficient, high-performance injectors. Efficient turbo machinery with wide operating range.

Parameter, Value:

Pump-fed LO_2, CH_4:

I_{sp}: 355+ seconds;

Thrust level: 30,000 lbf;

Operational life: 300+ seconds;

Number of restarts: 2;

Throttling: 10:1

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: In-space, descent, and ascent propulsion.

Capability Description: Provide planetary descent, ascent, and in-space transportation propulsion with high I_{sp} and the ability to throttle over a wide range of thrusts.

Capability State of the Art: Orbitial manuevering space engines using nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) with ablative combustion chambers.

Parameter, Value:

I_{sp}: 315.1 seconds;

Thrust level: 6,000 lbf;

Operational life: 100 missions

Capability Performance Goal: Provide wide-thrust operation for Mars or lunar surface descent.

Parameter, Value:

Pump-fed LO_2, CH_4:

I_{sp}: 360+ seconds;

Thrust level: up to 30,000 lbf;

Operational life: 300+ seconds;

Number of restarts: 2;

Throttling: 10:1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

2.1 Chemical Propulsion
2.1.2 Liquid Cryogenic

2.1.2.3 Liquid Oxygen (LO_2), Methane (CH_4) Reaction and Attitude Control Engine

TECHNOLOGY

Technology Description: Rocket engines for reaction control that use liquid methane as the fuel.

Technology Challenge: Methane as a propellant has not flown in an operational system. The system must have sufficient cryogenic fluid management to deliver the proper quality of propellant and demonstrate reliable ignition. The system should also be able to operate over a wide range of propellant qualities in pulse mode. The system must also demonstrate consistent peformance and reliability similar to existing state of the art (SOA), and operate as an integrated system with a main propulsion system.

Technology State of the Art: Altitude testing of 100-lbf reaction control technology demonstration engines.

Integrated Shuttle Orbiter Maneuvering System/reaction control system (RCS) operation on a terrestrial flying test bed.

Parameter, Value:

Liquid Oxygen (LO_2), Methane (CH_4):

Specific Impulse (I_{sp}): 317 seconds;

Thrust level: 100 lbf

TRL 4

Technology Performance Goal: Long-life, high-temperature combustion chambers.

Reliable ignition systems.

Efficient, high-performance injectors.

Reliable, high-repetition rate valves.

Parameter, Value:

LO_2, CH_4:

I_{sp}: 317 seconds;

Thrust level: 100 lbf;

Number of restarts: 25,000 valve cycles;

Impulse bit: 4 lbf-second;

Electronic Pulse Width: 80 msec

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reaction control propulsion integrated with main propulsion system.

Capability Description: Provide spacecraft reaction control and attitude control.

Capability State of the Art: Standalone, non-integrated reaction control systems using nitrogen tetroxide/monomethyl hydrazine (NTO/MMH).

Parameter, Value:

I_{sp}: 280-326 seconds;

Thrust level: 24-870 lbf;

Total life: 800 seconds

Capability Performance Goal: Provide reliable, long-life spacecraft reaction control propulsion that usews the same propellant tanks as the main propulsion system.

Parameter, Value:

LO_2, CH_4:

I_{sp}: 317 seconds (steady state);

Thrust level: 100-1000 lbf;

Number of restarts: 25,000 valve cycles;

Impulse bit: 4 lbf-second;

Electronic pulse width: 80 msec;

Common tank with main propulsion system (MPS);

Wide operating range with propellant qualities

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years

2.1 Chemical Propulsion
2.1.2 Liquid Cryogenic

2.1.2.4 Liquid Oxygen (LO_2), Liquid Hydrogen (LH_2) Reaction and Attitude Control Engine

TECHNOLOGY

Technology Description: Rocket engines for reaction and attiude control that use liquid hydrogen as the fuel. Thruster could also be used as primary propulsion for science missions.

Technology Challenge: Challenges include developing an engine that can meet the performance goals with flight quality hardware and demonstrated flight operations, reducing system complexity and dry mass, and managing cryogenic fluid.

Technology State of the Art: Altitude testing of 100-lbf reaction control technology demonstration engines.

Parameter, Value:
Liquid Oxygen (LO_2), Liquid Hydrogen (LH_2):
Thrust level: 100 lbf

TRL: 3

Technology Performance Goal: Long-life, high-temperature combustion chambers. Reliable ignition systems. Efficient, high-performance injectors. Reliable, high-repetition rate valves.

Parameter, Value:
LO_2, LH_2:
Specific impulse (I_{sp}): 317 seconds;
Thrust level: 100 lbf;
Number of restarts: 25,000 valve cycles

TRL: 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reaction control propulsion integrated with main propulsion system.

Capability Description: Provide spacecraft reaction control and attitude control.

Capability State of the Art: Reaction control systems using nitrogen tetroxide/monomethyl hydrazine (NTO/MMH).

Parameter, Value:
NTO/MMH:
I_{sp}: 280-326 seconds;
Thrust level: 24-870 lbf;
Total life: 800 seconds

Capability Performance Goal: Provide reliable, long-life spacecraft reaction control propulsion that can be integrated with the main propulsion system.

Parameter, Value:
LO_2, LH_2:
I_{sp}: 420+ seconds (steady state);
Thrust level: 100-1,000 lbf;
Number of restarts: 25,000 valve cycles

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enabling	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	5 years
Discovery: Discovery 14	Enhancing	--	2023	2020	5 years

2.1 Chemical Propulsion
2.1.3 Gels

2.1.3.1 Gelled and Metalized-Gelled Propellants

TECHNOLOGY

Technology Description: Micrometer/nanometer-sized particles are added to the fuel to deliver higher density and higher rocket specific impulse (I_{sp}).

Technology Challenge: Challenges include boil-off and corresponding shift in mixture ratio related to gellant-loading in the fuel and cryogenic fluid management issues.

Technology State of the Art: Nitrogen tetroxide (NTO)/ monomethyl hydrazine (MMH)/Aluminum chemical rocket engines used in missile tests. Gelled oxygen (O_2)/hydrogen (H_2) tested in lab-scale rocket engines demonstrated combustion. NTO/MMH, O_2/H_2 rocket.

Parameter, Value:

NTO/MMH/Aluminum:

I_{sp}: 325-335 seconds

TRL

4

Technology Performance Goal: Demonstrate boil-off reduction characteristics as well as increased I_{sp} and integrated system performance.

Parameter, Value:

Boil-off rate reduction: 25-50%;

I_{sp} increase: 25 seconds for NTO/MMH/Aluminum and 5-10 seconds for O_2/H_2/Aluminum;

Thrust: 1,000-5,000 pounds force (lbf)

TRL

7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Increased fuel density and I_{sp}, and reduced boil-off.

Capability Description: Increased fuel density and increased I_{sp} lead to increased space vehicle payload mass, as well as increased safety.

Capability State of the Art: NTO/MMH, O_2/H_2 rocket propulsion.

Parameter, Value:

I_{sp} NTO/MMH: 310 seconds;

I_{sp} O_2/H_2: 460 seconds

Capability Performance Goal: Metallized gelled propulsion can increase NTO/MMH I_{sp} by 25 seconds. O_2/H_2 I_{sp} increases 5 to 10 seconds. NTO/MMH, O_2/H_2 rocket.

Parameter, Value:

I_{sp} NTO/MMH to ~ 335 seconds;

I_{sp} O_2/H_2 to ~ 470 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	8 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	8 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	8 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enhancing	--	2029	2021	5 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.1 Chemical Propulsion
2.1.4 Solid

2.1.4.1 Solid Propulsion for Deep Space

TECHNOLOGY

Technology Description: Source of impulse for spacecraft. A rocket motor that uses solid propellants (fuel and oxidizer).

Technology Challenge: Challenges include evolving the technology to enable indefinite duration in-space use and improve vehicle mass fraction.

Technology State of the Art: Mixture of Aluminum/Ammonium Perchlorate/Hydroxyl-Terminated Polybutadiene.

Mass fraction: < 0.92.

Single, continous, non-extinguishable propellant consumption; propellant heater required to maintain propellant within thermal limits for operation.

Ammonium Perchlorate (AP) oxidizer that produces substantial amounts of hazardous Hydrogen Chloride (HCL).

Parameter, Value:

Speific impulse (I_{sp}) < 300 seconds, I_{sp} above 300 seconds only lab tested at coupon level;

Titanium motor casing; structurally non-optimized, fixed-length nozzles; after operation, igniter assembly carried essentially as payload.

TRL
4

Technology Performance Goal:

Propellant formulation having a higher I_{sp}.

Higher vehicle mass fraction.

Improved capability in thrust control and operation.

Develop an acceptable, environmentally-friendly propellant formulation.

Parameter, Value:

I_{sp}: > 300 seconds.

Vehicle mass fraction > 0.92: lower weight motor casing; structurally-optimized, extendable propellant exhaust nozzle; fully combusted/ejected igniter so that its weight is insignificant.

Extinguishable and restartable propellant consumption; propellant formulation that eliminates need for propellant heater.

Eliminate HCL from propellant exhaust.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Improved performance, operation, and cost for technology to be competitive with other in-space propulsion options.

Capability Description: Improved upper stage propellant I_{sp} performance. Improved vehicle mass fraction. Improved capability in thrust control and operation. Develop an acceptable, environmentally-friendly propellant formulation.

Capability State of the Art:

I_{sp} > 300 seconds only lab tested at coupon level.

Metal motor casing, nozzle length constrained by weight, large igniter system.

Non-extinguishable propellant consumption. The Long Duration Exposure Facility demonstrated that the solid propellant used in rocket motors age well in space. However, the propellant configuration cannot handle the stresses induced by temperature extremes.

AP is the oxidizer of choice in most solid rocket motors.

Parameter, Value:

I_{sp} < 300 seconds, I_{sp} above 300 seconds only lab tested at coupon level.

Titanium motor case, fixed-length nozzle, non-consummable igniter, carried as residual mass.

Single burn operation. Five-year storage demonstrated, but propellant heater required to prevent propellant from getting too cold and cracking.

When AP burns, it produces HCL. Phase Stabilized Ammonium Nitrate (AN) Composite and Ammonium Dinitramide (ADN) are alternates for AP. However, ADN is sensitive to shock and temperature and may detonate and AN has lower performance than AP.

Capability Performance Goal:

Propellant formulation having a higher I_{sp}.

Higher vehicle mass fraction.

Improved capability in thrust control and operation.

Develop an acceptable, environmentally-friendly propellant formulation.

Parameter, Value:

I_{sp} > 300 seconds.

Vehicle mass fraction > 0.92: lower weight motor casing; structurally optimized, extendable propellant exhaust nozzle; fully combusted/ejected igniter so that its weight is insignificant.

Extinguishable and restartable propellant consumption; propellant formulation that eliminates need for propellant heater;

HCL-free propellant exhaust that satisfies existing safety and performance levels of AP.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.1 Chemical Propulsion
2.1.5 Hybrid

2.1.5.1 Hybrid Propulsion for Space

TECHNOLOGY

Technology Description: A rocket motor that uses propellant in two different states of matter: one solid and the other either a liquid or gas.

Technology Challenge: Challenges include demonstrating long-term storage in space, conducting further fundamental fuel/oxidizer/additives/propellant-web design investigations, and conducting investigations of combined with burn rate additives, paraffin, different oxidizer flows, and multiport multi-layer configurations.

Technology State of the Art: Ground launch/airplane launch/booster launched, sub-orbital operation.

Vehicle mass fraction and propellant I_{sp} are less than that obtained with all liquid or solid propellant propulsion systems.

Single burn for most flight systems.

Parameter, Value:

Application dependent.

Mass fraction (MF) ~ 0.75, specific impulse (I_{sp}) ~ 280 seconds.

Earth atmosphere extended storage demonstrated. Ground systems have multiple starts, but require facility hookups or some change out of materials.

TRL

3

Technology Performance Goal: Fundamental fuel/oxidizer/additives/propellant-web design for long-duration, in-space use.

Increased mass fraction and I_{sp}.

Extend mission range of technology application.

Parameter, Value:

More than one-year storage in-space prior to use; -150° F, 100° F, vacuum storage

MF > ~0.90 and I_{sp} > 290 seconds.

Multiple re-start capability, extended in-space storage.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Alternate in-space propulsion technology utilizing very stable propellants having restartability, operation, and costs competitive with existing in-space propulsion options.

Capability Description: Propellant formulation for extended life and in-space use. Improved vehicle mass fraction and I_{sp}. Re-start/multiple firing use for upperstage operation.

Capability State of the Art: Multiple fuel/oxidizer combinations have been used; parafin, hydroxyl-terminated polybutadiene (HTPB), and aluminum-loaded HTPB with liquid oxygen (LO_2), nitrous oxide/hydroxyl-terminated polybutadiene (N_2O/HTPB), hydrogen peroxide/hydroxyl-terminated polybutadiene (H_2O_2/HTPB), sub-orbital operation.

Propellant Mass Fraction (MF and I_{sp} depend on above propellant formulations.

All flights to date have been single-burn, sub-orbital operation.

Parameter, Value:

Earth atmosphere extended storage, ground/ atmospheric launch, sub-orbital operation.

I_{sp} ~ 280 seconds, MF ~ 0.75.

Single burn.

Capability Performance Goal: Propellant formulation for extended life and in-space use; -150° F to +100° F, vacuum storage.

Higher I_{sp} and higher mass fraction.

Extend mission range of technology application by having multiple restarts.

Parameter, Value:

More than one-year storage in space prior to use.

Mass fraction > 0.90 and I_{sp} > 290.

Multiple burns, in-space ignition, in-space environment extended storage.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Explorer Class: Explorer Missions	Enabling	--	2023	2020	3 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.1 Chemical Propulsion
2.1.6 Cold Gas/ Warm Gas

2.1.6.1 Cold Gas/Warm Gas

TECHNOLOGY

Technology Description: Gas propulsion systems are typically used for small delta-V or when small total impulse is required; for example, attitude control of small spacecraft.

Technology Challenge: Flight validation of warm gas propulsion system to meet SmallSat mission-specific requirements.

Technology State of the Art: Cold gas technology is flying on a number of missions. Warm gas has been demonstrated in laboratory-relevant environments (vacuum and -50 to 150° F).

Parameter, Value:	TRL
Cold gas impulse is ~ 72 seconds	6

Technology Performance Goal: Improved specific impulse (I_{sp}) for SmallSat application.

Parameter, Value:	TRL
Warm gas impulse is ~135 seconds	8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Gas propulsion with higher I_{sp} resulting in larger mission delta-V.

Capability Description: Provides a compact gas propulsion system for small delta-V or when small total impulse is required; for example, attitude control of small spacecraft.

Capability State of the Art: Cold gas technology is flying on a number of missions.

Parameter, Value:

Cold gas impulse is ~ 72 seconds

Capability Performance Goal: Warm gas goal is to double the impulse of cold gas.

Parameter, Value:

Warm gas impulse is ~135 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.1 Chemical Propulsion
2.1.7 Micropropulsion

2.1.7.1 Solids

TECHNOLOGY

Technology Description: Solid motor microthrusters are miniature versions of large solid-booster rockets.

Technology Challenge: Optimization of the solid motor grain and burn-rate to meet mission-specific requirements.

Technology State of the Art: Flight qualified.

Parameter, Value: The technology is available.

TRL: 9

Technology Performance Goal: Each mission requiring a solid-propellant micropropulsion system will require tailoring.

Parameter, Value: Tailored delta-V profile

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Optimization of current technology for specific mission profile.

Capability Description: Solid motors provide precision impulse for deployments, attitude changes, spinup/spindown, etc.

Capability State of the Art: There are many solid motor options that have flown for micropropulsion applications from industry.

Parameter, Value:
Thrust: 170-800 N;
Specific impulse (I_{sp}): 240-270 s;
Burn rate profile: > 285 Newtons per second (N/s) total impulse

Capability Performance Goal: Meeting the mission-specific delta-V requirements.

Parameter, Value:
Thrust: 170-800 N;
I_{sp}: 240-270 s;
Burn rate profile: mission-specific (N/s)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.1 Chemical Propulsion
2.1.7 Micropropulsion

2.1.7.2 Cold Gas/Warm Gas

TECHNOLOGY

Technology Description: Micropropulsion cold/warm gas thrusters are miniature versions of devices described earlier.

Technology Challenge: Optimization of the thruster and propulsion system to meet CubeSat mission-specific requirements.

Technology State of the Art: Flight qualified.

Parameter, Value: The technology is already available.

TRL: 9

Technology Performance Goal: For each CubeSat mission the cold gas propulsion system will require tailoring.

Parameter, Value: Tailored delta-V profile, reduced subsystem volume and mass

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced size, weight, and power (SWaP) for CubeSat.

Capability Description: Cold/warm gas propulsion systems are used for precise attitude control and precision impulses.

Capability State of the Art: There are many cold/warm gas thrusters available that have flown for micropropulsion applications from industry.

Parameter, Value:

Cold gas: 0.1-25 N at < 120 seconds for hydrogen (H_2), helium (He), and nitrogen (N_2);

Warm gas: 180-245 seconds for hydrazine

Capability Performance Goal: Meeting the mission-specific delta-V requirements.

Parameter, Value:

Cold gas: 0.1-25 N at < 120 seconds for hydrogen (H_2), helium (He), and nitrogen (N_2);

Warm gas: 180-245 seconds for hydrazine.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.1 Chemical Propulsion
2.1.7 Micropropulsion

2.1.7.3 Monopropellant

TECHNOLOGY

Technology Description: Microthrusters using monopropellants are miniaturized versions of standard rocket engines that produce low thrust levels and minimum impulse bits for reaction control systems.

Technology Challenge: Development of small catalyzer beds, small high-speed flow control valves, thermal control techniques, and non-toxic alternative propellants.

Technology State of the Art: Flight qualified versions of hydrazine and hydrogen peroxide monopropellant microthrusters are already available.

Parameter, Value:

Thrust: ~1 N;
Specific impulse (I_{sp}): ~ 200-220 seconds;
Minimum Ibit: ~5,000 micro-Newton seconds (µNs)

TRL 9

Technology Performance Goal: A non-toxic variant of current monopropellant microthrusters with equivalent or better performance.
Reduce the minimum impulse bit for high-precision maneuvers.

Parameter, Value:

Thrust: > 1 N;
I_{sp}: > 200-220 secods;
Minimum Ibit: < 5,000 micro-Newton seconds (µNs)

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-toxic micropropulsion variant to reduce the overhead cost for CubeSat applications. Small impulse bits for precision spacecraft maneuvering.

Capability Description: Produce low-thrust levels and minimum impulse bits for reaction control systems.

Capability State of the Art: There are many hydrazine thrusters that have flown for micropropulsion applications from industry.

Parameter, Value:

MR-103H:
Thrust: 1.07 N;
I_{sp}: 220 seconds;
Power: 6.5 W;
Minimum Ibit: 5,000 micro-Newton seconds (µNs);
Mass: 195 grams

Capability Performance Goal: Equivalent or better performance to current systems in a non-toxic variant. Increased precision in the impulse bits.

Parameter, Value:

Thrust: > 1 N;
I_{sp}: > 220 seconds;
Minimum Ibit: < 5,000 micro-Newton seconds (µNs)

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.1 Ion Thrusters

TECHNOLOGY

Technology Description: Ion thrusters are electrostatic thrusters that use a variety of plasma generation techniques to ionize a large fraction of propellant. High voltage grids then extract the ions from the plasma and electrostaticly accelerate them to high velocity at voltages up to and exceeding 10 kV.

Technology Challenge: Challenges include improving thrust-to-power ratio of state of the art (SOA) and higher-power operation while achieving sufficient lifetime. Integrated power processing unit drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: Thruster testing in vacuum environment with associated power processing unit:

- NASA Evolutionary Xenon Thruster (NEXT) ion thruster;
- Nuclear Electric Xenon Ion System (NEXIS) ion thruster

Multiple optics configurations have been examined in laboratory thrusters.

Parameter, Value:

NEXT ion thruster has been operated at > 50,000 hours in a relevant environment at 6.9 kW, 4,100 seconds, 236 mN, 69% efficiency;

NEXIS ion thruster has been operated at 13-28 kW, 6,000-8,500 seconds, 0.4-.53N, 75-83% efficiency

TRL 5

Technology Performance Goal: Increasing power levels while maintaining or improving specific impulse (I_{sp}), efficiency, wide throttle range, and life.

Parameter, Value:

High-power Ion thrusters: 20-100 kW;

Lifetimes: > 50,000 hours;

I_{sp}: > 4,000 seconds;

Thrust-to-power ratio: > 60 mN/kW

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low mass, long-life, very-high delta-V primary propulsion.

Capability Description: Provides very high delta-V prime propulsion for robotic spacecraft within the solar system, and delta-V sufficient to provide long-life (10 years or more), large robotic scientific, cargo, or crew logistics missions. This technology can also be used to provide attitude control, precision pointing, and momentum dumping for both science missions and human exploration missions.

Capability State of the Art: Xenon gridded ion propulsion system hardware is used for orbit insertion as well as on-orbit station keeping on commercial communications satellites. The NASA Solar Technology Application Readiness (NSTAR) thruster has been used as primary propulsion for the Dawn mission.

Parameter, Value:

NSTAR: 2.3 kW, 3,100 seconds, 87 mN, 55% efficiency;

4.5 kW-class gridded ion: 4.5 kW, 3,600 seconds, 168 mN, 65% efficiency

Capability Performance Goal: Higher power and higher I_{sp} for cargo delivery and science mission or higher power and higher thrust for crew logistics propulsion with long lifetime and broad throttlability.

Parameter, Value:

High-power Ion thrusters: 20-100 kW;

Lifetimes: > 50,000 hours;

I_{sp}: > 3,000 seconds;

Delta-V: > 5 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	2 years
Discovery: Push	Enhancing	--	--	--	2 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.2 Hall Thrusters

TECHNOLOGY

Technology Description: Hall thrusters are electrostatic thrusters that use a cross-field discharge described by the Hall effect to generate and accelerate the plasma.

Technology Challenge: Challenges include scaling to high-power and higher specific impulse (I_{sp}), and achieving sufficient lifetime. Integrated power processing unit drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: 10 to 15 kW technology development unit. 50 to 100 kW laboratory unit. 100 kW proof of concept nested channel laboratory unit.

Parameter, Value:

15 kW with 60% efficiency and 3,000 seconds I_{sp};
50 kW with ~60% efficiency and 2,400 seconds I_{sp};
60 kW with 65% efficiency and 2,500 seconds I_{sp}

TRL
3

Technology Performance Goal: Near-term objective is to mature 10 to 15 kW system to flight and continue to explore higher power levels and long life for exploration missions to Mars and beyond.

Parameter, Value:

Power: 10 to 100 kW;
I_{sp}: to 3,000 seconds;
Life: to 50,000 hours;
Power Processing Unit input voltage: > 200 V

TRL
4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low mass, long-life, very-high delta-V primary propulsion.

Capability Description: Provides very high delta-V prime propulsion for robotic spacecraft within the solar system, and delta-V sufficient to provide long-life (10 years or more), large robotic scientific or cargo missions. This category of propulsion capability can also be used to provide attitude control, precision pointing, and momentum dumping for both science missions and human exploration missions.

Capability State of the Art: Hall thruster systems are used for prime propulsion for deep space science missions, station keeping of communications satellites, attitude control, momentum dumping, and are used for low-thrust delivery to geosynchronous orbit to increase delivered mass.

Parameter, Value:

Power: 0.2 to 4.5 kW;
I_{sp}: 1,390 to 2,030 seconds;
Thrust: 13 to 252 mN;
Efficiency: 40 to 55%;
Propellant: Xenon;
Demonstrated life up to 10,000 hours

Capability Performance Goal: Higher power and higher I_{sp} for cargo delivery and science mission or higher power and higher thrust for crewed logistics propulsion with long lifetime and broad throttlability.

Parameter, Value:

Lifetime: > 50,000 hours;
I_{sp}: 2,000 to 3,000 seconds;
Power: > 10 kW;
Delta-V: > 5 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	3 years
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	1 year
New Frontiers: Trojan Tour and Rendezvous	Enhancing	--	2024	2016	1 year
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	1 year
New Frontiers: Io Observer	Enhancing	--	2029	2021	1 year

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.3 Pulsed Inductive Thruster

TECHNOLOGY

Technology Description: Pulsed electrode-less electric thruster that can operate on multiple propellants and that can be scaled to higher power by increasing the repetition rate.

Technology Challenge: Challenges include increasing the power throughput of a pulsed inductive thruster while increasing efficiency through inductive energy recapture. This involves: capacitors for fast repetition rate; reliable, high-pulse-rate valves; life-limiting thermal loads on coil face, and operation on a variety of propellants. An integrated power processing unit drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: Laboratory level, 1 meter diameter, 18-capacitor pulsed inductive thruster; MkV with all capacitors spark gap switch tested on multiple propellants.

Parameter, Value:	TRL
Specific impulse (I_{sp}) is 3,000 to 8,000 seconds at 4-4.5 kJ/pulse	3

Technology Performance Goal: Increasing power levels while maintaining or improving I_{sp}, efficiency, wide throttle range, and life.

Parameter, Value:	TRL
Power levels: 200 kWe at 70%; I_{sp}: 3,000 to 10,000 seconds	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low mass, long-life, very high delta-V primary propulsion.

Capability Description: Provides very high delta-V prime propulsion for robotic spacecraft within the solar system, and delta-V sufficient to provide long-life (10 years or more), large robotic scientific or cargo missions.

Capability State of the Art: Xenon gridded ion propulsion system equipment is used for orbit insertion as well as on-orbit station keeping on commercial communications satellites. The NASA Solar Technology Application Readiness (NSTAR) thruster has been used as primary propulsion for deep space missions. Hall thruster for station keeping and as primary propulsion during mission recovery operation.

Parameter, Value:

NSTAR: 2.3 kW, 3,100 seconds, 87 mN, 55% efficiency;

4.5 kW-class gridded ion: 4.5 kW, 3,600 seconds, 168 mN, 65% efficiency;

Hall thruster: 4.5 kW, 2,030 seconds, 252 mN, 55% efficiency

Capability Performance Goal: Higher power and higher I_{sp} for cargo delivery and science mission or higher power and higher thrust for crewed logistics propulsion with long lifetime and broad throttlability.

Parameter, Value:

High-power Ion thrusters: 20 to 100 kW;

Lifetimes: > 50,000 hours;

I_{sp}: > 3,000 seconds;

Delta-V: > 5 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years
Explorer Class: Explorer Missions	Enhancing	--	2029	2026	7 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.4 Magnetoplasmadynamic (MPD) Thruster

TECHNOLOGY

Technology Description: Provides thrust by the interaction of high currents with either applied magnetic fields or a self-induced magnetic field to accelerate ionized propellant.

Technology Challenge: Challenges include limitations on component lifetime, thermal management, and performance, as well as achieving performance on a variety of propellants. Integrated power processing unit drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: Self- and applied-magnetic field laboratory model thrusters have been tested in pulsed (megawatts input power) and steady-state modes (tens to hundreds of kW).

Parameter, Value:

Thrust: 10s Newtons;

Specific impulse (I_{sp}): 1,000 to 10,000 seconds;

Thruster efficiencies generally below 40%, although hydrogen (H_2) and Lithium (Li)-fed thrusters have efficiency > 50%

TRL

3

Technology Performance Goal: Increasing power levels while maintaining or improving I_{sp}, efficiency, wide throttle range, and life (or achieving significant life).

Parameter, Value:

Process 200 to 250 kW input power, demonstrate 60% thruster efficiency, and component lifetime in excess of 10 khr.

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-mass, long-life, very high delta-V primary propulsion.

Capability Description: Provides very high delta-V prime propulsion for robotic spacecraft within the solar system, and delta-V sufficient to provide long-life (10 years or more), large robotic scientific or cargo missions.

Capability State of the Art: Xenon gridded ion propulsion system equipment is used for orbit insertion as well as on-orbit station keeping on commercial communications satellites. The NASA Solar Technology Application Readiness (NSTAR) thruster has been used as primary propulsion for deep space missions. Hall thruster for staton keeping and as primary propulsion during mission recovery operation.

Parameter, Value:

NSTAR: 2.3 kW, 3,100 seconds, 87 mN, 55% efficiency;

4.5 kW-class gridded ion: 4.5 kW, 3,600 seconds, 168 mN, 65% efficiency;

Hall thruster: 4.5 kW, 2,030 seconds, 252 mN, 55% efficiency

Capability Performance Goal: Higher power and higher I_{sp} for cargo delivery and science mission or higher power and higher thrust for crewed logistics propulsion with long lifetime and broad throttlability

Parameter, Value:

High-power Ion thrusters: 20 to 100 kW;

Lifetimes: > 50,000 hours;

I_{sp}: > 2,000 seconds;

Delta-V: > 5 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	6 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years
Explorer Class: Explorer Missions	Enabling	--	2029	2026	7 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.5 Electrospray Propulsion

TECHNOLOGY

Technology Description: Provides thrust using a conductive fluid and electrostatic fields to extract and accelerate charged droplets, clusters of molecules, or individual molecules or ions.

Technology Challenge: Challenges are scaling high-efficiency thrusters down to centimeter-level diameters or Micro Electro Mechanical Systems (MEMS) fabrication of large tip arrays so they can be mounted like standard reaction control thrusters (e.g., as are used for attitude and rendezvous/docking control); micro-thrust and amplitude-modulation to avoid "ringing" precision payloads and to achieve sub-centimeter position control and tens of milliarcsecond attitude control without reaction wheels; and narrow plumes, low-contamination propellant to avoid harmful impingement, development of power processing systems, and developing systems for long-duration operation.

Technology State of the Art: MEMS- and porous media-based thrusters with ionic liquids or metals prototypes are in development and testing.

Parameter, Value:

Specific impulse (I_{sp}): ~ 1,000 seconds;
Thrust: > 100 microNewtons (µN);
Power: < 10 W;
System efficiency: ~ 50%;
System mass: < 100 grams;
System volume: < 100 cm^3;
Thruster lifetime: < 100 hours

TRL
4

Technology Performance Goal: Obtaining high I_{sp} with low power operation and extended lifetime operation in a small form factor (e.g., CubeSat).

Parameter, Value:

I_{sp}: > 1,500 seconds;
Thrust: > 100 µN;
Power: < 10 W;
System efficiency: > 70%;
System mass: < 100 grams;
System volume: < 100 cm^3;
Thruster lifetime: > 500 hours;
Plume half-angle: < 10 degrees;
Low-contamination propellant

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-I_{sp} micropropulsion for primary propulsion, formation flight, and attitude actuation for distributed, coupled spacecraft.

Capability Description: Provide primary propulsion for small spacecraft (of particular interest are 3U-6U spacecraft) or precision 6 Degrees of Freedom (DOF) actuation needed to achieve sub-centimeter and sub-arcsec spacecraft bus performance with low vibrations for interferometric and phased array payloads that control to fewer than tens of nanometers with constant thrusting over years, and without contaminating neighboring spacecraft with exhaust plumes.

Capability State of the Art:
Limited delta-V for small spacecraft < 100 m/sec. Thruster options: (1) Large discrete capillary emitters with a regulated propellant supply. Flight qualified thrusters have been delivered. (2) Micro pulsed plasma thrusters with solid Teflon was flown. (3) Cold gas thrusters.

Parameter, Value:

Pulsed plasma thruster I_{sp}: 443 seconds;
Cold gas thruster I_{sp}: < 100 seconds

Capability Performance Goal: Small satellite (e.g. CubeSat) primary propulsion system that provides significant increase in delta-V over state of the art. Performance needed for large phased arrays with a free-flying secondary. Requirements slightly relaxed from levels for astrophysics missions.

Parameter, Value:

Delta-V: > 500 m/second;
I_{sp}: > 1,500 seconds;
Plume half-angle: < 15 degrees;
Low-contamination propellant

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Strategic Missions: Push	Enhancing	--	--	--	2 years
Explorer Class: Explorer Missions	Enhancing	--	2023	2020	2 years
Discovery: Push	Enhancing	--	--	--	2 years
New Frontiers: Push	Enhancing	--	--	--	2 years
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years
Strategic Missions: Large UV/Visible/IR Surveyor Mission	Enabling	--	2035*	2030	15 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.6 Wave Drive Thrusters

TECHNOLOGY

Technology Description: Wave-driven concepts like the wave-driven heilicon and Ponderomotive thrusters. For example, the helicon concept provides thrust by forming plasmas with radio frequency (RF) discharge in an axial magenetic field to develop a helicon wave.

Technology Challenge: Challenges are lightweight power circuits, magnetic nozzle development, micro RF plasma sources, and lifetime. Multiple propellant options have yet to be explored. Integrated power processing unit drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: Proof of concept laboratory experiments.

Parameter, Value:

Specific impulse (I_{sp}): ~ 1,000 to 1,400 seconds;
Thrust: ~ 1 mN;
Power: < 30 W;
Power/thrust: ~ 30 W/mN;
Thruster lifetime: unknown

TRL
3

Technology Performance Goal: Obtaining high I_{sp} with low power operation and extended lifetime operation in a small form factor (e.g. CubeSat).

Parameter, Value:

I_{sp}: > 1,000 seconds;
Power: < 100 W;
Thrust: > 2 mN;
System efficiency: > 50%;
Thruster lifetime: > 500 hours

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-I_{sp} micropropulsion.

Capability Description: Provide primary propulsion for small spacecraft. Spacecraft in the 3U-180 kilogram range are of particular interest.

Capability State of the Art:

Limited delta-V for small spacecraft < 100 m/sec.
Thruster options:

- Micro pulsed plasma thrusters with solid Teflon has already flown.
- Cold gas thrusters

Parameter, Value:

Pulsed plasma thruster I_{sp}: 443 seconds;
Cold gas thruster I_{sp}: < 100 seconds

Capability Performance Goal: Small satellite (e.g. CubeSat) primary propulsion system that provides significant increase in delta-V over state of the art.

Parameter, Value:

Delta-V: > 500 m/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	7 years
Explorer Class: Explorer Missions	Enhancing	--	2029	2026	7 years
Discovery: Later Discovery Program	Enabling	--	2026	2023	7 years
New Frontiers: Push	Enhancing	--	--	--	7 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.7 Miniature Hall Thruster

TECHNOLOGY

Technology Description: Hall thrusters are electrostatic thrusters that use a cross-field discharge described by the Hall effect to generate and accelerate the plasma.

Technology Challenge: Significant thruster technical challenges at < 200 W, cathode considerations, and power processing unity (PPU) mass/volume considerations.

Technology State of the Art: Proof of concept laboratory experiments.

Parameter, Value:

Specific impulse (I_{sp}): 1,200 to 2,000 seconds;
Power: 50 to 170 W;
Thrust: 3 to 6 mN;
System efficiency: unknown;
Thruster lifetime: unknown

TRL 4

Technology Performance Goal: Obtaining high I_{sp} with low power operation and extended lifetime operation in a small form factor (e.g. CubeSat).

Parameter, Value:

I_{sp}: > 1,500 seconds;
Thrust: < 5 mN;
Power: < 100 W;
System efficiency: > 70%;
Thruster lifetime: > 500 hours

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-I_{sp} micropropulsion.

Capability Description: Provide primary propulsion for small spacecraft. Spacecraft in the are 6U to 180 kilogram range are of particular interest.

Capability State of the Art: A 200 W Hall thruster has already flown.

Parameter, Value:

I_{sp}: ~ 1,390 seconds;
Thrust: 13 mN (at 200 W);
Power: 100 to 300 W;
System efficiency: unknown;
Thruster lifetime: unknown

Capability Performance Goal: Small satellite (e.g. CubeSat) primary propulsion system that provides significant increase in delta-V over state of the art.

Parameter, Value:

Delta-V: > 500 m/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years
Explorer Class: Explorer Missions	Enabling	--	2023	2020	5 years
Discovery: Discovery 14	Enabling	--	2023	2020	5 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enabling	--	2029	2021	5 years
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.8 Miniature Ion Thruster

TECHNOLOGY

Technology Description: Provide thrust by a variety of plasma generation techniques to ionize a large fraction of the propellant. High-voltage grids then extract the ions from the plasma and electrostaticly accelerate them to high velocity at voltages up to and exceeding 10 kV.

Technology Challenge: Significant thruster technical challenges at < 200 W, cathode considerations, cathode-less configurations, micro radio frequency (RF) plasma sources, and power processing unit (PPU) mass/volume considerations.

Technology State of the Art: Proof of concept laboratory experiments.

Parameter, Value:

Specific impulse (I_{sp}): > 1,800 to 2,800 seconds;
Thrust: < 5 mN;
Power: < 10 to 100 W;
System efficiency: unknown;
Thruster lifetime: unknown

TRL: 4

Technology Performance Goal: Obtaining high I_{sp} with low power operation and extended lifetime operation in a small form factor (e.g. CubeSat).

Parameter, Value:

I_{sp}: > 1,500 seconds;
Thrust: < 5 mN;
Power: < 100 W;
System efficiency: > 70%;
Thruster lifetime: > 500 hours

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-I_{sp} micropropulsion.

Capability Description: Provide primary propulsion for small spacecraft. Spacecraft in the are 6U to 180 kilogram range are of particular interest.

Capability State of the Art:

Limited delta-V for small spacecraft: < 100 m/sec
Thruster options:

- A micro pulsed plasma thruster with solid Teflon has already
- Cold gas thrusters

Parameter, Value:

Pulsed plasma thruster I_{sp}: 443 seconds;
Cold gas thruster I_{sp}: < 100 seconds

Capability Performance Goal: Small satellite (e.g. CubeSat) primary propulsion system that provides significant increase in delta-V over state of the art.

Parameter, Value:

Delta-V: > 500 m/sec

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	5 years
Explorer Class: Explorer Missions	Enabling	--	2023	2020	5 years
Discovery: Discovery 14	Enabling	--	2023	2020	5 years
New Frontiers: New Frontiers 5 (NF5/~2022 AO Release)	Enabling	--	2029	2021	5 years
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.9 Resistojets

TECHNOLOGY

Technology Description: Resistojets use an electrically-heated element in contact with the propellant to increase the enthalpy prior to expansion through a nozzle.

Technology Challenge: Optimization of the thruster and propulsion system to meet SmallSat mission-specific requirements.

Technology State of the Art: Flight qualified systems exist at scale appropriate for full size satellites.

Parameter, Value: Technology available.

TRL: 9

Technology Performance Goal: Resistojet propulsion system will require tailoring CubeSat missions.

Parameter, Value: Tailored thrust and specific impulse (I_{sp})

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced size, weight, and power (SWaP) for CubeSat missions.

Capability Description: Provides attitude control, precision pointing, and momentum dumping for both science missions and human exploration missions.

Capability State of the Art: Resistojets are commercially available in the 500 to 900 W range.

Parameter, Value:
I_{sp}: 294 to 303 seconds;
Thrust: 0.18 to 0.8 N

Capability Performance Goal: Power levels less than 500 W tailored for specific mission.

Parameter, Value:
I_{sp}: state of the art;
Thrust: < 0.18 N

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.10 Arcjets

TECHNOLOGY

Technology Description: Arcjets use an electric arc to heat the propellant prior to expansion through a nozzle.

Technology Challenge: Optimization of the thruster and propulsion system to meet SmallSat mission-specific requirements.

Technology State of the Art: Flight qualified systems exist at scale appropriate for full size satellites.

Parameter, Value: Technology available — **TRL** 9

Technology Performance Goal: Resistojet propulsion system will require tailoring CubeSat missions.

Parameter, Value: Tailored thrust and specific impulse (I_{sp}) — **TRL** 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reduced size, weight, and power (SWaP) for CubeSat missions.

Capability Description: Provides attitude control, precision pointing, and momentum dumping for both science.

Capability State of the Art: Arcjets are mature flight technology at the 2,000 W level for station keeping applications.

Parameter, Value:
I_{sp}: 500 to 615 seconds;
Thrust: 0.2 to 0.26 N

Capability Performance Goal: Power levels less than 2,000 W tailored for specific mission.

Parameter, Value:
I_{sp}: state of the art;
Thrust: < 0.2 N

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.2 Non-Chemical Propulsion
2.2.1 Electric Propulsion

2.2.1.11 Variable Specific Impulse Magnetoplasma Rocket (VASIMR)

TECHNOLOGY

Technology Description: Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high-power radio frequency (RF) driven plasma thruster capable of specific impulse (I_{sp})/thrust modulation at constant input power scalable over a broad range of power levels using highly efficient power processing units (PPUs) based on existing commercial radio broadcast technology.

Technology Challenge: Challenges include specific mass, heat rejection, thermal control, interactions of the divergent plume with the spacecraft, and life qualification. Integrated PPU drives cost, schedule, and risk for flight system implementation.

Technology State of the Art: Current laboratory test hardware is capable of processing 200 kW of input power through a superconducting plasma thruster. I_{sp} values from 3,000 to 5,000 seconds have been demonstrated with efficiencies that range from 50 to 70% processing a number of propellant options.

Parameter, Value:

Power: 30 kW to 200 kW;

Variable I_{sp}: 2,000 to 5,000 seconds;

Thrust: 900 to 5,900 mN;

Efficiency: 72% at 5,000 seconds;

Propellant: Argon or Krypton;

Magnetic shielding: no wear measurable after > 10K shots;

Design goal: > 50,000 hours

TRL

3

Technology Performance Goal: Immediate objective is thermal steady-state ground testing up to 100 kW per thruster. Near-term objective is maturation of a 30 to 200 kW-capable dual thruster system to flight demonstration for solar-powered cislunar space tug operations, and exploration to Mars and Jupiter's icy moons.

Parameter, Value:

VF-200 (2 x TC-1 thrusters):

Power: 30 kW to 200 kW;

I_{sp}: 2,000 to 5,000 seconds;

Thermal steady-state and lifetime ground testing with > 50K hours lifetime goal;

Eventually scaling to megawatt (MW) class power levels to support human flight operations

TRL

5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low mass, long-life, very-high delta-V primary propulsion.

Capability Description: Provides very high delta-V prime propulsion for robotic spacecraft within the solar system and delta-V sufficient to provide long-life (10 years or more), large robotic scientific or cargo missions.

Capability State of the Art: Xenon gridded ion propulsion system equipment is used for orbit insertion as well as on-orbit station keeping on commercial communications satellites. The NASA Solar Technology Application Readiness (NSTAR) thruster has been used as primary propulsion for deep space missions. Hall thrusters are used for station keeping and as primary propulsion during mission recovery operations.

Parameter, Value:

NSTAR: 2.3 kW, 3,100 seconds, 87 mN, 55% efficiency;

Xenon system: 4.5 kW, 3,600 seconds, 168 mN, 65% efficiency;

Hall thruster: 4.5 kW, 2,030 seconds, 252mN, 55%

Capability Performance Goal: Higher power and higher I_{sp} for cargo delivery and science mission or higher power and higher thrust for crewed logistics propulsion with long lifetime and broad throttlability.

Parameter, Value:

Delta-V: > 5 km/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years

2.2 Non-Chemical Propulsion
2.2.2 Solar and Drag Sail Propulsion

2.2.2.1 Solar Sail Propulsion

TECHNOLOGY

Technology Description: Solar sails provide thrust by reflecting light, using no propellant to provide thrust.

Technology Challenge: Challenges include low areal density; space-durable, reflective membrane materials; large-area membrane manufacturing and handling processes; ultra-large membrane deployment technologies; lightweight, high packaging efficiency deployable booms; high-performance spinning architectures; and reliable autonomous deployment.

Technology State of the Art: A solar sail developed by a foreign government is being used to navigate a small spacecraft within the inner solar system near the orbit of Venus. The U.S. has conducted a 20 m x 20 m ground system level demonstration.

Parameter, Value:

Foreign space agency: 14 m x 14 m, 300 micron thickness

U.S.: 20 m x 20 m, 3 micron thickness

TRL: 5

Technology Performance Goal: Ultra-large area, deployable, low areal density reflective membrane structures for high delta-V destinations and continuous thrusting mission applications.

Parameter, Value:

1st generation: 40 m x 40 m, areal density: 10-25 g/m^2;

2nd generation: 150 m x 150 m, areal density: < 10 g/m^2;

3rd generation: 300 m x 300 m

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Ultra-lightweight flexible materials, see 12.1.3.2

CAPABILITY

Needed Capability: Low mass, long-life, very-high delta-V propulsion.

Capability Description: Need highly efficient propellantless propulsion:

1st generation: for spacecraft positioned sub L1;

2nd generation: to reach the inner solar system and raise inclination to 75 degrees or higher;

3rd generation: to enable rapid transit to > 250 AU

Capability State of the Art: There is no existing U.S. solar sail propulsion capability. The SOA for systems providing this capability are the Dawn mission solar electric propulsion (SEP) system and a foreign space agency's solar sail.

Parameter, Value:

Foreign space agency system: 14 m x 14 m;

Dawn specific impulse (I_{sp}): 3,100 seconds

Capability Performance Goal: Provide very high delta-V for small robotic spacecraft within the inner solar system:

1st generation: (~1 AU) delta-V sufficient to create a long-life (10 years or more), artificial Lagrange Point sub-L1 that allows a spacecraft to station keep along the Sun/Earth line.

2nd generation: (~0.25 AU to ~2 AU) delta-V sufficient to place a long-life (10 years or more), spacecraft in a heliocentric orbit with semi-major axis of 0.48 AU at inclination of 75 degrees or higher.

3rd generation: (~0.25 AU to ~5 AU) delta-V sufficient to enable a Voyager class spacecraft to reach 250 AU within 20 years of launch.

Parameter, Value:

Delta-V: > 20 km/s

Delta-V: > 30 km/s

Delta-V: > 40 km/s

Lifetime: > 10 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Solar Terrestrial Probes: Push	Enhancing	--	--	--	3 years
Solar Wind Measurements	Enabling	--	On-going*	--	2 years
Suborbital: Science, Research & Technology (Suborbital Program)	Enabling	--	On-going	--	2 years

2.2 Non-Chemical Propulsion
2.2.2 Solar and Drag Sail Propulsion

2.2.2.2 Drag Sail Propulsion

TECHNOLOGY

Technology Description: Drag sails provide thrust by changing the ballistc coefficient of a spacecraft, increasing atmospheric drag. Drag enhancement systems can assist in the end-of life disposal of a spacecraft.

Technology Challenge: Challenges include developing lightweight deployable booms, and conducting system integration and testing in the space environment.

Technology State of the Art: NanoSail-D2 demonstrated that sail drag enhancement technologies can accelerate spacecraft deorbit. A commercial sail has been launched and will provide a similar demonstration once it deploys.

Parameter, Value:	TRL
3.5 m x 3.5 m sail deployed in Earth orbit	6

Technology Performance Goal: Deployed sail area required is variable and spacecraft dependent.

Parameter, Value:	TRL
16 m^2	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-mass primary propulsion system for de-orbit applications.

Capability Description: Provide very high delta-V for Earth orbiting spacecraft, allowing reliable, low-mass end-of-life deorbit.

Capability State of the Art: Currently performed by chemical propulsions systems.

Parameter, Value:

Relatively high mass penalty

Capability Performance Goal: Need low-mass end-of-life propulsion for spacecraft deorbit.

Parameter, Value:

Delta-V: > 88 m/s through increasing drag area, sufficient for deorbit from altitudes up to 400 km [ballistic coefficient (m/cda) ~30.9];

Storage lifetime: > 10 years;

Operational lifetime: < 1 year

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Push	Enhancing	--	--	--	2 years

2.2 Non-Chemical Propulsion
2.2.3 Thermal Propulsion

2.2.3.1 Solar Thermal Propulsion (STP)

TECHNOLOGY

Technology Description: Sunlight is captured with a large area concentrator and focused inside an absorber cavity to heat material to extremely high temperatures. The heat is transferred to the propellant and provides high specific impulse (I_{sp}) at low thrust.

Technology Challenge: Challenges include improving optical concentrator accuracy and performance (from 50-60% to 85-90%), system/stage packaging, sun pointing, inflatable deployment, and controlled cryogenic boil-off. Solar thermal propulsion (STP) is limited by payload shroud volume when considering liquid hydrogen for propellant. An option to overcome this limit involves utilizing high temperature carbides with melting point ~4,000 K.

Technology State of the Art: Much work was done on STP in the 1990s with concepts of both direct-gain and thermal storage. Work was done on various thruster designs, concentrators, cryogenic hydrogen storage, and power conversion. Variations on basic STP include use of fiber optics to decouple the concentrator from the spacecraft, and investigating miniaturized STP for CubeSats.

Parameter, Value:
I_{sp}: ~700-860 seconds;
Optical quality 50-60% efficient

TRL 4

Technology Performance Goal: Low thrust with higher I_{sp} to reduce the propellant volume required for the mission. The optical quality of the solar concentrators is also increased.

Parameter, Value:
Thrust: 2 to 4 lbf;
I_{sp}: 1,200 seconds;
Concentrator optical quality: improvement to 85-90%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Extremely high-temperature materials compatible with the propellant and lightweight, highly-reflective material that withstands effects of the space environment. See TA 12.1.4 and TA 12.3.

CAPABILITY

Needed Capability: High I_{sp}, low-to-moderate thrust main propulsion.

Capability Description: Provides low thrust and high I_{sp} to allow larger mass payloads with slightly longer trip times than chemical propulsion for small-medium single launch missions in Earth/Moon space.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:
I_{sp}: 280 to 316 seconds

Capability Performance Goal: Compared to chemical propulsion, demonstrate higher I_{sp} to reduce the amount of propellant required and tank size, providing more shroud volume for the payload customer.

Parameter, Value:
I_{sp}: > 900 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years

2.2 Non-Chemical Propulsion
2.2.3 Thermal Propulsion

2.2.3.2 Nuclear Thermal Propulsion (NTP)

TECHNOLOGY

Technology Description: Solid core nuclear thermal propulsion (NTP) engines use a fission reactor in the thrust chamber to heat large mass flow of propellant to extremely high temperatures for high specific impulse (I_{sp}) at high thrust.

Technology Challenge: Challenges include designing reactor fuel to operate at higher hydrogen exhaust temperatures, use reduced quantities of highly-enriched uranium, and minimize fission product release. Fuel erosion in hot hydrogen is also a challenge. Other challenges include ground test engines that affordably use either borehole, fully-contained, or scrubbed engine exhaust options that meet current environmental regulations and developing engine system designs and other engine components to meet critical mission requirements.

Technology State of the Art: NASA programs in the 1960s and 1970s developed NTP to a prototype flight design. Current modifications to fuel forms and materials have reduced the Teachnology Readiness Level (TRL) to 3.

Parameter, Value:

A NASA program ground tested 20 rocket reactors with thrust levels ranging from 25 to 250 klbf, including hydrogen exhaust tempertures of 2,550 K, and single engine with 27 restarts. Two engines demonstrated ~850 second I_{sp} for long steady burn durations (20 to 62 minutes).

TRL

4

Technology Performance Goal: High thrust with higher I_{sp} to reduce the numer of Space Launch System (SLS) launches. Other design requirements based on the worst case for a range of missions.

Parameter, Value:

Thrust: 25,000 lbf;

I_{sp}: 900 seconds;

Longest single burn: 46 minutes;

Cumulative burn time: 85 to 102 minutes (depending on mission scenario);

Four start-ups, shortest time between burns: 5 hours (may increase to minimize Xe135 poisoning)

TRL

8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Materials capable of withstanding the extremely high temperatures, dense radiation from neutrons and gamma rays, and exposure to the hydrogen. See TA 12.1.4.

CAPABILITY

Needed Capability: High I_{sp}, high-thrust main propulsion.

Capability Description: Provides high thrust and high I_{sp} for reduced mission times and reduced initial mass in low-Earth orbit (IMLEO) for human missions to Mars and other destinations.

Capability State of the Art: No flight NTP capability exists. High-thrust main propulsion state of the art is NTO/MMH chemical rocket engines.

Parameter, Value:

NTO/MMH I_{sp}: 280 to 316 seconds

Capability Performance Goal: High I_{sp} to reduce the trip time and/or reduce the number of SLS launches. Trade off high I_{sp} with reactor fuel endurance to meet mission requirements.

Parameter, Value:

High thrust with I_{sp}: ~900 seconds using hydrogen as propellant.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	7 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	7 years

2.2 Non-Chemical Propulsion
2.2.4 Tether Propulsion

2.2.4.1 Electrodynamic Tether Propulsion

TECHNOLOGY

Technology Description: Electrodynamic tethers provide thrust by using a current-carrying wire to interact with a planetary magnetosphere via the Lorentz Force.

Technology Challenge: Challenges with 1st and 2nd generation systems include: long-life tether, and high-voltage, high-current control algorithms. Challenges with 3rd generation systems include: long-life tether; high-voltage, high-current control algorithms; and tether system deployment and dynamics.

Technology State of the Art: The 20-km Tethered Satellite System demonstrated high power operation in low-Earth orbit (LEO) operating at power levels sufficient to have generated > 100 m/s delta-V.

Parameter, Value:	TRL
< 20 km length, operating at ~1 ampere (A) for < 1 day	5

Technology Performance Goal: Long, lightweight, conducting tether propulsion system.

Parameter, Value:	TRL
1st generation (derived parameters): 1 km length, operating at < 1 A, for weeks; 2nd generation (derived parameters): > I km length, > 1 A for months to years; 3rd generation (derived parameters): > 1 km length, > 5 A for months to years	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low mass, long-life, very-high delta-V propulsion.

Capability Description: Provide highly efficient propellantless propulsion:

1st generation: for satellite end-of-life de-orbit;

2nd generation: for LEO station keeping and maneuvering;

3rd generation: for Jovian exploration

Capability State of the Art: There is no existing tether propulsion capability. The state of the art for a system providing a similar capability is the Dawn mission solar electric propulsion (SEP) system.

Parameter, Value:

Dawn I_{sp}: 3,100 seconds

Capability Performance Goal: Provide very high delta-V for robotic spacecraft within planetary magneospheres.

1st generation: delta-V sufficient to de-orbit from altitudes up to 2,000 km.

2nd generation: delta-V sufficient to maintain a spacecraft at a 400 km altitude for 5 years.

3rd generation: delta-V sufficient to electrocapture and maneuver in the Jovian system for 2 years.

Parameter, Value:

1st generation: > 100 m/s;

2nd generation: > 1,500 m/s;

3rd generation: > 3,000 m/s

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Earth Systematic Missions: Push	Enhancing	--	--	--	2 years
Solar Terrestrial Probes: Push	Enhancing	--	--	--	3 years
New Frontiers: Push	Enhancing	--	--	--	6 years

2.2 Non-Chemical Propulsion
2.2.4 Tether Propulsion

2.2.4.2 Momentum Exchange Tether Propulsion

TECHNOLOGY

Technology Description: Rotating tethers create a controlled force on the end-masses of the system due to centrifugal acceleration. While the tether system rotates, the objects on either end of the tether will experience continuous acceleration; the magnitude of the acceleration depends on the length of the tether and the rotation rate. Momentum exchange occurs when an end body is released during the rotation. The transfer of momentum to the released object will cause the rotating tether to lose energy, and thus lose velocity and altitude. Using electrodynamic tether thrusting or ion propulsion, the system can then re-boost itself with little or no expenditure of consumable reaction mass.

Technology Challenge: Challenges include rendezvous with the tether tip during rotation, precision orbital propagation analysis from release, and reusabillty.

Technology State of the Art: Expendable systems have been demonstrated in space, and laboratory experiments and modeling have been conducted.

Parameter, Value:	TRL
< 20 km	4

Technology Performance Goal: Long, lightweight, rotating, controlled tether system.

Parameter, Value:	TRL
Up to 100 km length. Stable and predictable tether dynamics and tether tip control for automated rendezvous.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Autonomous rendezvous and docking. See TA 4 Robotics and Autonomous Systems (specifically, Section 4.6).

CAPABILITY

Needed Capability: Low-mass, long-life, very-high delta-V, reusable Earth escape propulsion.

Capability Description: Provide reusable Earth escape and orbit transfer capability infrastructure for sustained exploration and science beyond low-Earth orbit (LEO).

Capability State of the Art: Does not exist.

Parameter, Value:
Does not exist.

Capability Performance Goal: Provide Earth escape impulse, repeatedly, to multiple independent spacecraft without the use of propellant.

Parameter, Value:
Characteristic energy > 0.1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Discovery: Later Discovery Program	Enhancing	--	2026	2023	8 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.1 Beamed Energy Propulsion

2.3.1.1 Beamed Energy Propulsion

TECHNOLOGY

Technology Description: Beamed energy propulsion uses laser or microwave energy from a ground- or space-based energy source and beams it to an orbital vehicle, which uses it to: 1) heat a propellant, or 2) reflect beamed energy to generate momentum.

Technology Challenge: Challenges include the need for a very large ground- or space-based beamed energy source with adaptive, real-time optics and tracking, as well as advanced ceramic composite, cooling, and optic technology. Developing a propellant feed and heat exchanger system is also a challenge.

Technology State of the Art: Very small scale demonstration achieved free flight to 230 ft with 10 kW pulse laser. Laboratory component work has been done for planetary orbit transfer.

Parameter, Value:

Specific impulse (I_{sp}): ~500 seconds

TRL: 2

Technology Performance Goal: Achieve orbit modification using power beaming approach (e.g., for a CubeSat). Utilize more dense propellants with low average molecular weights.

Parameter, Value:

I_{sp}: > 500 seconds

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Very large ground- or space-based beamed energy source. See TA 3.3.4.2.

CAPABILITY

Needed Capability: Propulsion energy source not on spacecraft to faciliate higher I_{sp} and increase payload mass fraction.

Capability Description: Utilize power provided by a ground- or space-based station(s) to beam energy to a spacecraft to provide kinetic energy and vary vehicle velocity.

Capability State of the Art: Liquid oxygen (LO_2)/liquid hydrogen (LH_2) used on Centaur upperstage with 464 seconds I_{sp}.

Parameter, Value:

Payload mass fraction: 0.08

Capability Performance Goal: Low thrust, high I_{sp}, no onboard power source for propulsion. Increase transfer vehicle payload mass fraction.

Parameter, Value:

Payload mass fraction: 0.425

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	5 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.2 Electric Sail Propulsion

2.3.2.1 Electric Sail Propulsion

TECHNOLOGY

Technology Description: Provide thrust by reflecting charged particles from long, charged wires extended from a spacecraft in the solar wind, using no propellant to provide thrust.

Technology Challenge: Challenges include maintaining wire deployment and control during flight and high-voltage/wire phasing for thrust control.

Technology State of the Art: Laboratory experiments and modeling; electrodynamic tether heritage is directly applicable.

Parameter, Value: (TRL 3)

Up to 20 km-length antennas and tethers have been deployed in space.

Technology Performance Goal: Array of long, thin wires deployed by centrifugal force from a central spacecraft and demonstrated thrust.

Parameter, Value: (TRL 6)

> 4, multi-kilometer wires (number and length are mission-dependent);

Thrust: > 0 lbf

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-mass, long-life, very-high delta-V primary propulsion.

Capability Description: Need highly efficient, propellantless propulsion to enable rapid transit to ~ 250 AU.

Capability State of the Art: There is no existing electric sail propulsion capability. The state of the art for systems providing this capability are a foreign government's solar sail.

Parameter, Value:

14 m x 14 m;

specific impulse (I_{sp}): 3,100 seconds

Capability Performance Goal: Provide very high delta-V for small robotic spacecraft within the inner solar system (~1 AU to ~7 AU). Specifically, delta-V sufficient to enable a Voyager-class spacecraft to reach 250 AU within 20 years of launch.

Parameter, Value:

Delta-V: > 40 km/s;

Trip time: < 20 years;

Lifetime: > 10 years

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Solar Terrestrial Probes: Push	Enhancing	--	--	--	3 years
Solar Wind Measurements	Enhancing	--	On-going*	--	3 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.3 Fusion Propulsion

2.3.3.1 Fusion Propulsion

TECHNOLOGY

Technology Description: Fusion propulsion utilizes fusion energy to generate thrust or electric power for other propulsion concepts. Configurations can operate in steady state or repetitive pulse modes.

Technology Challenge: Fusion reactor operation – achieve sufficient balance of plasma confinement time, density. and temperature to achieve energy gain; Conversion of fusion energy to useful jet power (magnetic nozzle design); Systems complexity with concepts using Tritium; Electrical power generation, transfer, and storage of high MW to GW levels with minimal losses; Thermal and nucler radiation material effects; and Initialization energy source (fission reactor, solar, battery, etc.).

Technology State of the Art: 50 years of fusion research with magnetically-confined and/or inertial confinement configurations. The following fusion propulsion concepts were investigated with analysis and experiments:

- Gas Dynamic Mirror
- Magnetized Target Fusion
- Inertial Electrostatic Confinement (IEC)
- Spherical Torus

Parameter, Value:	TRL
Specific impulse (I_{sp}): 10,000 to 100,000 seconds; Thrust: 4 to hundreds of kN	2

Technology Performance Goal: Demonstrate a fusion propulsion concept in a laboratory environment and measure performance parameters.

Parameter, Value:	TRL
I_{sp}: 10,000 to 100,000 seconds; Jet power to Gigawatts; Thrust: 4 to hundreds of kN	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High I_{sp} and low-to-moderate thrust main propulsion.

Capability Description: Provides primary propulsion systems for spacecraft missions with very high delta-V and rapid transit times.

Capability State of the Art:

Parameter, Value:

I_{sp}: 280 to 316 seconds

Capability Performance Goal: Need low-to-moderate thrust and high I_{sp} propulsion to provide high delta-V with low mass.

Parameter, Value:

I_{sp}: > 10,000 seconds;

Thrust: > 4 kN;

Fusion energy gain (Q): 10 to 100

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	13 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.4 High Energy Density Materials

2.3.4.1 Metallic Hydrogen

TECHNOLOGY

Technology Description: High energy density, extremely high pressure (> 1,000,000 pounds per square inch (psi)) state of hydrogen that has large amounts of stored chemical energy (with complex chemical structures or atoms stored in frozen solid cryogenic molecular matrices).

Technology Challenge: Upgrading existing experimental equipment is required, as well as increasing the ability to generate and store.

Technology State of the Art: Tiny amounts created in diamond anvil cell at millions of psi.

Parameter, Value:	TRL
Specific impulse (I_{sp}): 1,000 to 2,000 seconds	1

Technology Performance Goal: Demonstrate controlled storage of metallic hydrogen.

Parameter, Value:	TRL
Meta-stable storage < 1,000,000 psi.	2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Research on techniques to establish the physical conditions to produce and then store metallic hydrogen.

CAPABILITY

Needed Capability: High-effiiciency primary propulsion for interplanetary missions.

Capability Description: Main Propulsion System (MPS) with revolutionary increases in rocket engine I_{sp} and many-fold increases in vehicle payload mass.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:

I_{sp}: 280 to 310 seconds

Capability Performance Goal: MPS with high thrust and high I_{sp}.

Parameter, Value:

I_{sp}: 1,000 to 2,000 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	20 years
Planetary Flagship: Push	Enhancing	--	--	--	20 years
Discovery: Push	Enhancing	--	--	--	20 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.4 High Energy Density Materials

2.3.4.2 Atomic Boron/Carbon/Hydrogen

TECHNOLOGY

Technology Description: Atomic boron, carbon, and hydrogen have large amounts of stored chemical energy (with complex chemical structures or atoms stored in frozen cryogenic molecular matrices or solid cryogens).

Technology Challenge: Challenges include upgrading existing experimental equipment is required, as well as increasing the ability to generate and store atomic species in a frozen cryogen.

Technology State of the Art: Gram quantities have been created.

Parameter, Value:	**TRL**
Hydrogen I_{sp}: 750 to 1,500 seconds; Boron I_{sp}: 500 to 700 secconds; Carbon I_{sp}: 500 to 700 seconds	2

Technology Performance Goal: Demonstrate controlled storage of atomic species in large quantities and high weight percent.

Parameter, Value:	**TRL**
Storage of kilograms with > 15 weight percent atomic species in solid cryogen	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High effiiciency primary propulsion for interplanetary missions.

Capability Description: Main propulsion system with revolutionary increases in rocket engine I_{sp} and many-fold increases in vehicle payload mass.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:

I_{sp}: 280 to 310 seconds

Capability Performance Goal: MPS with high thrust and high specific impulse (I_{sp}).

Parameter, Value:

Thrust: 1,000 to 5,000 lbf;

Hydrogen I_{sp}: 750 to 1,500 seconds;

Boron I_{sp}: 500 to 700 secconds;

Carbon I_{sp}: 500 to 700 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	20 years
Planetary Flagship: Push	Enhancing	--	--	--	20 years
Discovery: Push	Enhancing	--	--	--	20 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.4 High Energy Density Materials

2.3.4.3 High Nitrogen Compounds (N_4+, N_5+)

TECHNOLOGY

Technology Description: High-nitrogen compounds have large amounts of stored chemical energy (with complex chemical structures or atoms in metastable room-temperature chemical solids). These are the most powerful chemical explosives ever created.

Technology Challenge: Challenges include upgrading existing experimental equipment, as well as increasing the ability to generate and store. Additional challenges include high shock sensitivity, fabrication, transportation, ground processing, and personnel safety.

Technology State of the Art: Gram quantities have been created.

Parameter, Value: | **TRL**
Specific impulse (I_{sp}): 500 to 600 seconds | 2

Technology Performance Goal: Demonstrate controlled storage of high-nitrogen species in large quantities.

Parameter, Value: | **TRL**
Storage of ~ kilogram quantities of high nitrogen compound. | 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-efficiency primary propulsion for interplanetary missions.

Capability Description: The propellant is a monopropellant with a theoretical I_{sp} of 500 to 600 seconds.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:
I_{sp}: 280 to 310 seconds

Capability Performance Goal: MPS with high thrust and high I_{sp}.

Parameter, Value:
Thrust: 1,000 to 5,000 lbf;
I_{sp}: 500 to 600 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Flagship: Push	Enhancing	--	--	--	20 years
Discovery: Push	Enhancing	--	--	--	20 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.5 Antimatter Propulsion

2.3.5.1 Antimatter Propulsion

TECHNOLOGY

Technology Description: Antimatter propulsion is based on conversion of a large percentage (up to ~75%) of fuel mass into propulsive energy by annihilation of atomic particles with their antiparticles.

Technology Challenge: Single particle annihilations are well understood and have been verified experimentally. Bulk annihilation experiments are less well understood, and need experimental data. Antiprotons are currently generated and stored at high energy on beam lines. However, experiments need lower energy, beam compression, and focus while maintaining population to approximate application. Experiments need to be performed at a production facility; hardware would need to be develped to process antiproton beams and interface with target geometries. Target geometry needs to be developed and manufactured.

Technology State of the Art: Matter-antimatter interactions are routinely used in high-energy science experiments and medical applications. Limited production capability exists. To date, no proof-of-principle experiments have been performed to demonstrate any type of propulsion applications. At one laboratory, hundreds to thousands of antiprotons have been briefly stored in Penning style traps and tens of antihydrogen atoms has been produced and briefly stored.

Parameter, Value:	TRL
Specific impulse (I_{sp}): > 13,500 seconds	2

Technology Performance Goal: Proof-of-principle experiment to demonstrate propulsive application (i.e., antimatter on target to produce energy for propulsion). The target geometry would be dependent on the concept approach and could range from a catalyzed fission/fusion pellet to formed sail type material.

Parameter, Value:	TRL
I_{sp}: > 100,000 seconds	2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Research and development of antimatter generation and storage.

CAPABILITY

Needed Capability: Extremely high I_{sp} and low-moderate thrust primary propulsion enabling short trip times around the solar system and interstellar precursors.

Capability Description: Provides primary propulsion systems for spacecraft in the multiple megawatt power levels and higher (likely outer-solar system class missions with rapid transit or interstellar precursors; e.g., 1,000 AU).

Capability State of the Art: No flight antimatter propulsion technology exists. High-thrust main propulsion state of the art is Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:

I_{sp}: 280 to 316 seconds

Capability Performance Goal: Need extremely high I_{sp}, low-to-moderate thrust, high performance propulsion to provide high delta-V with low mass.

Parameter, Value:

I_{sp}: > 100,000 seconds; Thrust to weight ratio: > $10e^{-3}$

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	13 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.6 Advanced Fission

2.3.6.1 Gas and Liquid Core Nuclear Thermal Propulsion

TECHNOLOGY

Technology Description: Gas and liquid core nuclear thermal propulsion (NTP) is similar to solid core NTP except the fission reactor core is either gaseous or liquid. Two gas core concepts have been investigated. The open cycle concept relies on fluid dynamics or electromagnetics to contain the reactor core and minimize fuel loss. The closed cycle concept relies on a transparent wall to contain the nuclear fuel and uses a seeded propellant. Liquid core concepts rotate the molten reactor fuel.

Technology Challenge: Open cycle challenges include steady-state fuel containment, engine cooling, transient start-up/shut down, acceptable system thrust/weight, and how to ground test and determine environmentally safe orbit for startup. The major closed cycle challenge includes transparent wall resistance to high temperatures, radiation, and erosion. Liquid core challenges include high-temperature materials, understanding mass transfer from molten fuel surface, stability of liquid layer, heat transfer, and side effects of any liquid core rotations.

Technology State of the Art: Much work was done on liquid core open cycle and closed cycle (nuclear light bulb) gas core technology in the 1960s and 1970s with a lot of associated analyses. Additionally, small-scale, non-nuclear cold flow and hot flow experiments demonstrated flow containment and energy coupling. More recent computational fluid dynamics analyses and system modeling have been conducted.

Parameter, Value:	TRL
Integrated system performance predictions: Open cycle thrust: 50,000 lbf and Specific impulse (I_{sp}) of 3,000 seconds; Closed cycle thrust: 92,000 lbf and I_{sp} of 1,870 seconds; Liquid core thrust: 9,000 lbf and I_{sp} of 1,500 seconds.	3

Technology Performance Goal: Higher I_{sp} than solid core NTP. Advance from analytical and experimental proof-of-concept to component or breadboard validation for open cycle and closed cycle concepts.

Parameter, Value:	TRL
Open cycle thrust: 50,000 lbf and I_{sp} of 3,000 seconds; Closed cycle thrust: 92,000 lbf and I_{sp} of 1,870 seconds; Liquid core thrust: 9,000 lbf and I_{sp} of 1,500 seconds	4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fundamental model development/analysis coupled with testing of highly energetic plasmas and fissile material. High-temperature materials withstanding extremely high temperatures, dense radiation from neutrons and gamma rays, and exposure to hydrogen. See TA 12.1.4.

CAPABILITY

Needed Capability: High-I_{sp}, high-thrust main propulsion.

Capability Description: Provides high thrust and an I_{sp} 2 to 3 times that of solid core nuclear thermal propulsion, allowing shorter trip times.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:

I_{sp}: 280 to 316 seconds

Capability Performance Goal: Achieve I_{sp} needed for shorter trip times to Mars and other solar system destinations.

Parameter, Value:

I_{sp}: > 1,500 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	13 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.6 Advanced Fission

2.3.6.2 Fission Fragment Propulsion

TECHNOLOGY

Technology Description: The high kinetic energy (~3-5% the speed of light) of ionized fission fragments is guided with a magnetic nozzle and directly used to produce thrust or used indirectly to heat a propellant for higher thrust.

Technology Challenge: The primary challenge is to provide a nuclear fuel with enough density to allow a greater chance of fission from neutrons or provide a reflector with high efficiency to keep the neutrons in use for multiple passes through the fuel. A fuel that is too dense will capture the fission fragment kinetic energy and increase system temperature. Waste heat and radiation environment must be included in the design. A method to efficiently heat the propellant and an environmentally safe orbit to start the engine releasing primarily fission products have yet to be determined.

Technology State of the Art: Numerous studies on fission fragment concepts have been conducted since the 1980s. These studies examined rotating disk or dusty plasma reactors using a magnetic nozzle to direct the fission fragments.

Parameter, Value:	TRL
Thrust: 10 lbf; Specific impulse (I_{sp}): 527,000 seconds	2

Technology Performance Goal: Increase usefulness by indirectly heating a propellant and providing more thrust at reduced I_{sp}. More work analytical system studies are needed, as well as an experimental proof of concept.

Parameter, Value:	TRL
Thrust: 10 to 1,000 lbf; I_{sp}: 30,000 to 527,000 seconds	3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: High-temperature materials that can withstand the extremely high temperatures, dense radiation from neutrons and gamma rays, and exposure to hydrogen. See TA 12.1.4.

CAPABILITY

Needed Capability: Extremely high I_{sp}, moderate-thrust main propulsion.

Capability Description: Provides primary propulsion capable of shorter trip times and initial mass in low-Earth orbit (IMLEO) reduction.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:

I_{sp}: 280 to 316 seconds

Capability Performance Goal: Achieve extremely high I_{sp} needed for shorter trip times to Mars and other solar system destinations.

Parameter, Value:

I_{sp}: > 30,000 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	13 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.6 Advanced Fission

2.3.6.3 External Pulsed Plasma Propulsion

TECHNOLOGY

Technology Description: Small directional nuclear pulse units are ejected at the aft end of the spacecraft and detonated. Thrust is produced by momentum exchange with a large pusher plate and shock absorbers on the aft end of the spacecraft.

Technology Challenge: Technology challenges include type of pulse unit, degree of collimation, detonation position and fissile burn-up fraction, pusher plate plasma interaction, shock absorber efficiency, timing, dynamic response, and environmentally safe orbit to startup.

Technology State of the Art: The concept originated in the late 1950s and early 1960s and had a lot of system analysis and simulated non-nuclear ground test demonstrations. A number of other concept studies were conducted looking at electromagnetic pusher plates and alternate ignition concepts.

Parameter, Value:
Thrust: 500,000 lbf;
Specific impulse (I_{sp}): 5,000 seconds

TRL 2

Technology Performance Goal: High I_{sp} and high thrust for large spacecraft. More work is needed with analytical system studies and experimental proof-of-concept.

Parameter, Value:
Thrust: 500,000 lbf;
I_{sp} of 5,000 seconds

TRL 3

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Pusher plate withstanding loads and radiation exposure.

CAPABILITY

Needed Capability: High thrust and high I_{sp} primary propulsion that provides shorter trip times.

Capability Description: Provides shorter trip times for large-scale human exploration of the outer solar system.

Capability State of the Art: Nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) chemical rocket engines.

Parameter, Value:
I_{sp}: 280 to 316 seconds

Capability Performance Goal: High thrust and high I_{sp} needed for the fastest trip times to the outer solar system (for large-scale mission capability).

Parameter, Value:
I_{sp}: > 5,000 seconds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: Push	Enhancing	--	--	--	13 years

2.3 Advanced (TRL <3) Propulsion Technologies
2.3.7 Breakthrough Propulsion

2.3.7.1 Breakthrough Propulsion

TECHNOLOGY

Technology Description: Breakthrough propulsion is applied scientific research specifically looking for propulsion breakthroughs from emerging physics.

Technology Challenge: Challenges include scaling of thrust and achieving high energy densities, eliminating all sources of mimicry (false positives), and attaining high quality.

Technology State of the Art: Advanced vacuum thrusters: demonstrated thrust in the 100 micro-Newton range using high-fidelity torsion pendula, and in the 1 to 100 milli-Newton range with strain gauge force measurement systems. Applied scientific research (using interferometry approaches) to detect an indication of changes in optical properties associated with the presence of energy density distributions is being pursued at multiple labs in industry, government, and academia to demonstrate microscopic instance of space warp or worm hole.

Parameter, Value:	**TRL**
Awaiting emerging physics results.	1

Technology Performance Goal: Generating > 1mN of thrust on a high-fidelity thrust stand in a vacuum environment. Generating statistically significant change in optics properties within a controlled region on an interferometer that indicates a change in space time.

Parameter, Value:	**TRL**
Thrust: 1 mN; Thrust to power of ~ 0.1 N/kW; Change optics properties of at least 1/100th a wavelength of electromagnetic source	1

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Long-life, ultra-high delta-V primary propulsion and rapid transit solutions capable of reaching ultra-distant destinations.

Capability Description: Provides extremely capable and flexible primary propulsion systems developed from applied scientific research exploring the nature of space-time, gravitation, inertial frames, quantum vacuum, and other fundamental physical phenomena.

Capability State of the Art: Technology does not yet exist.

Parameter, Value:

Technology does not yet exist.

Capability Performance Goal: Proof-of-principle.

Parameter, Value:

Demonstration of the proposed physical phenomena under controlled laboratory conditions.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years
New Frontiers: Push	Enhancing	--	--	--	10 years
Planetary Flagship: Push	Enhancing	--	--	--	10 years

2.4 Supporting Technologies
2.4.2 Propellant Storage and Transfer

2.4.2.1 Passive Thermal Control for Cryogenic Propellants

TECHNOLOGY

Technology Description: Advanced insulation, solar shields, low conductivity structure, thermodynamic venting, and vapor cooling to reduce the heat load entering the tank that causes boil-off.

Technology Challenge: Attachment/support of thick, multi-layer insulation, > 5 m diameter tank that can survive launch loads and meet thermal goal; scaling of low conductivity structure; vapor cooling efficiency (including para-to-ortho conversion, LH_2 only).

Technology State of the Art: Thick multi-layer insulation blankets > 45 reflectors; fiberglass composite structure ground tested.

Parameter, Value:

Demontrated in ground testing:

Duration: > 2 weeks;

Tank size: < 3 m diameter;

Integrated tank heat load: liquid hydrogen (LH_2): 0.65 W/m^2 (220 K environment); liquid oxygen (LO_2): ~ 0.67 W/m^2 (liquid methane (LCH_4) test in 250 K environment)

TRL: 5

Technology Performance Goal: Low-propellant heat leak resulting in low boil-off suitable for very large in-space propellant tanks.

Parameter, Value:

Loiter duration: > 2 weeks;

Tank size: > 5 m diameter;

Integrated tank heat load: LH_2 < 0.65 W/m^2 (220 K environment); LO_2: < 0.7 W/m^2 (250 K environment)

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Long-duration cryogenic propellant storage.

Capability Description: Reduce heat loads and resulting boil-off to enable multi-day loiter in low-Earth orbit (LEO).

Capability State of the Art: Few layers of multi-layer insulation, high-conductance structures.

Parameter, Value:

Loiter duration: < 9 hours

Capability Performance Goal: Long-duration cryogenic stage loiter time for LH_2 propellant tank > 5 m diameter.

Parameter, Value:

Loiter duration: > 1 week

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	4 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	4 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

2.4 Supporting Technologies
2.4.2 Propellant Storage and Transfer

2.4.2.2 Active Thermal Control

TECHNOLOGY

Technology Description: Integrates cryocooling with the propellant tank system to reduce or eliminate the heat load entering the tank that causes boil-off.

Technology Challenge: 1st generation liquid hydrogen (LH_2): Scale-up of cryocooler components without increasing integration losses.

1st generation liquid oxygen (LO_2): Scale-up of cryocooler components without increasing integration losses (note that LO_2 system would directly address challenges of liquid methane (LCH_4) storage).

2nd generation LH_2: > 20x increase of heat removal capacity of 20 K flight type cryocooler; cryocooler efficiency increase.

Technology State of the Art: Active thermal control has been tested at subscale sizes on the ground.

Parameter, Value:

1st generation LH_2: 60% reduced boil off of LH_2, ground demonstrated at 1.3 m tank scale (0.3 W/m² at 220 K environment);

1st generation LO_2: zero boil-off of LO_2, demonstrated at 1.3 m tank scale (-1.0 W/m² at 220 K environment);

2nd generation LH_2: hydrogen zero boil-off demonstrated in a low-fidelity ground test

TRL: 4

Technology Performance Goal: Active thermal control to:

1st generation LH_2: reduce heat leak to large LH_2 tank.

1st generation LO_2: eliminate heat leak to LO_2 propellant tank.

2nd generation LH_2: eliminate tank heat flux to LH_2 propellant.

Parameter, Value:

1st generation LH_2: > 4 m tank diameter; < 1.2 W/m² heat flux;

1st generation LO_2: > 3 m tank diameter; zero net heat flux;

2nd generation LH_2: > 4 m tank diameter; zero net heat flux

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Long- or indefinite-duration cryogenic propellant storage.

Capability Description: In-space vehicle propellant storage in excess of a year.

Capability State of the Art: Few layers of multi-layer insulation, high conductance structures; cryocoolers have flown to cool telescope detectors (much lower cooling requirement).

Parameter, Value:

Loiter of < 9 hours

Capability Performance Goal: In-space vehicle propellant storage of sufficient duration to support planetary exploration; ultra low average heat flux to propellant.

Parameter, Value:

Storage duration for LH_2 and O_2 > 1 year;

1st generation LH_2: < 0.03 W/m² heat flux;

1st generation LO_2: 0.00 W/m² heat flux;

2nd generation LH_2: 0.00 W/m² heat flux

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 6 Crewed to NEA	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

2.4 Supporting Technologies
2.4.2 Propellant Storage and Transfer

2.4.2.3 In-Space Tank-to-Tank Propellant Transfer

TECHNOLOGY

Technology Description: High-efficiency line and tank chill-down, followed by no-vent transfer and fill of a receiving propellant tank.

Technology Challenge: Challenges include unsettled propellant state in storage and receiver tanks; maintaining flow rate to high-recever tank level; and automation.

Technology State of the Art: Limited ground test data for optimized chill down and no-vent fill.

Parameter, Value:

Transfer time: ~ 4 hours;

Chill-down propellant loss: < ~25%;

Fill level achieved: > 90%

TRL 4

Technology Performance Goal: No-vent fill to achieve > 95% fill level. In-space demonstration.

Parameter, Value:

No-vent fill to 95%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Cryogenic propellant transfer.

Capability Description: Propellant can be transferred from a tanker or depot to an in-space propulsion stage; the potential to fill or top off propulsion stage tanks can maximize in-space delta-V.

Capability State of the Art: Storable propellant transferred from Progress to the International Space Station and during missions by other government agencies.

Parameter, Value:

A bladder supply tank is used to separate the pressurant from liquid.

Capability Performance Goal: In-space cryogenic propellant transfer with minimal propellant consumption.

Parameter, Value:

Transfer time, chill-down propellant loss; fill level achieved on receiving tank without venting.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	5 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

2.4 Supporting Technologies
2.4.2 Propellant Storage and Transfer

2.4.2.4 In-Space Propellant Gauging

TECHNOLOGY

Technology Description: Accurate measurement of cryogenic liquid propellant quantity in space without propulsive settling maneuvers.

Technology Challenge: Fluid to be measured is in an unsettled state and cryogenic, which is a challenge.

Technology State of the Art: Radio frequency mass gauging has been demonstrated through subscale ground and parabolic aircraft testing.

Parameter, Value:
Uncertainty in ground testing: < 1%;
Uncertainty in parabolic aircraft test: < 3%

TRL 5

Technology Performance Goal:
Accurate measurement without settling propellant.
In-space demonstration.

Parameter, Value:
Bond number: < 1;
Uncertainty: < 3%;
System weight: < 0.1% of propellant

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Unsettled propellant gauging.

Capability Description: Ensures that a propulsion stage has adequate propellant to complete the mission before departing. Can monitor propellant losses due to boil-off.

Capability State of the Art: Propulsive thrusters are used to actively settle the propellant and a liquid “level” is measured using one of several options.

Parameter, Value:
Acceleration yielding bond number > 1;
No propellant slosh;
Uncertainty: < 0.5%;
System mass: estimated < 2 kg

Capability Performance Goal: Accurate gauging; low mass and power impact.

Parameter, Value:
Bond number: < 1;
Uncertainty: < 3%;
Mass: < 3 kg

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	3 years
Exploring Other Worlds: DRM 6 Crewed to NEA	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	3 years
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enabling	2027	2027	2021	3 years
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	3 years